Neutrinoless double beta decay beyond the "lobster" plot and its connection to cosmology

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ACFI Snowmass Workshop 2020

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DFG Deutsche Forschungsgemeinschaft

Neutrinos – what do we know?

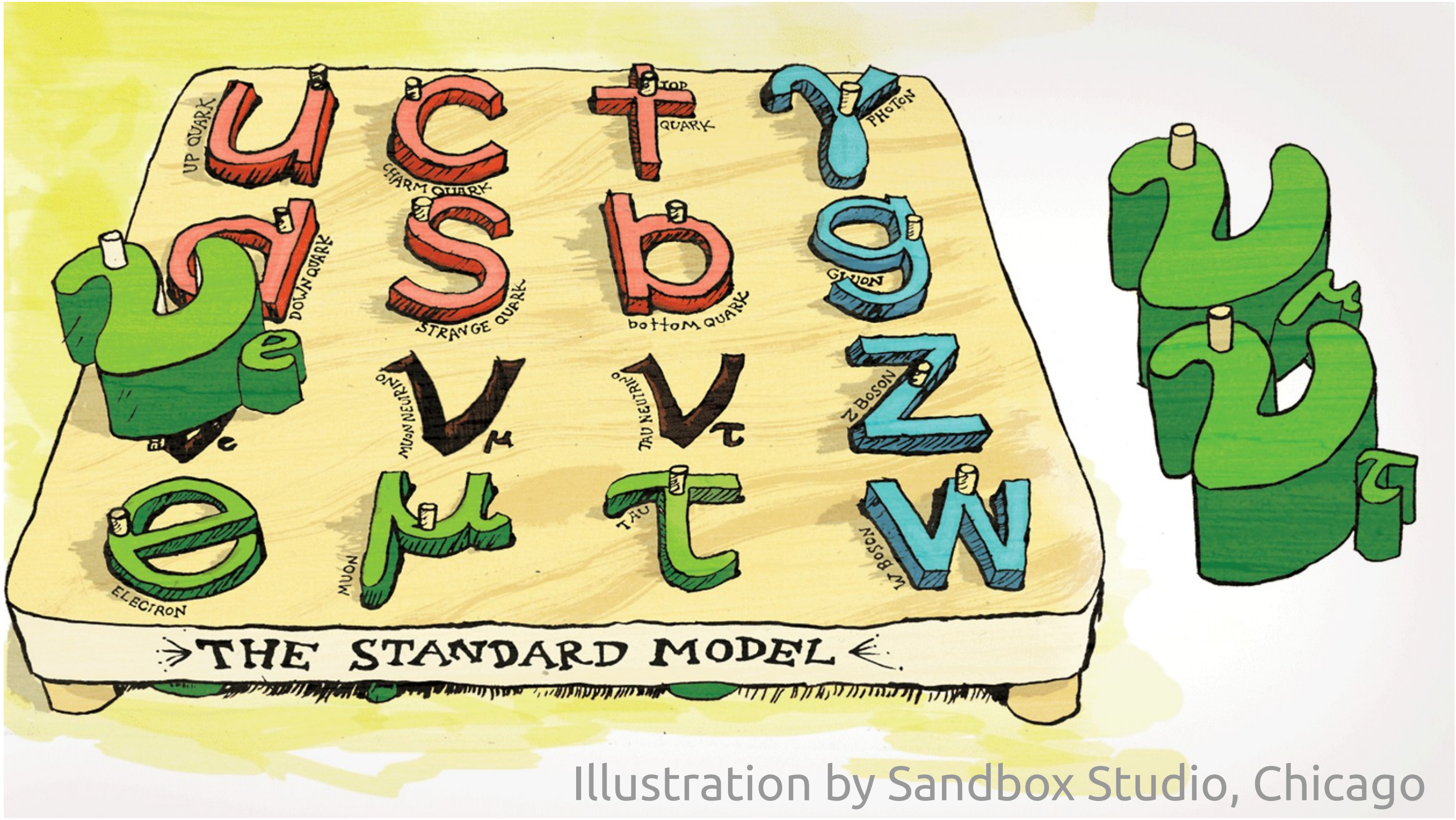
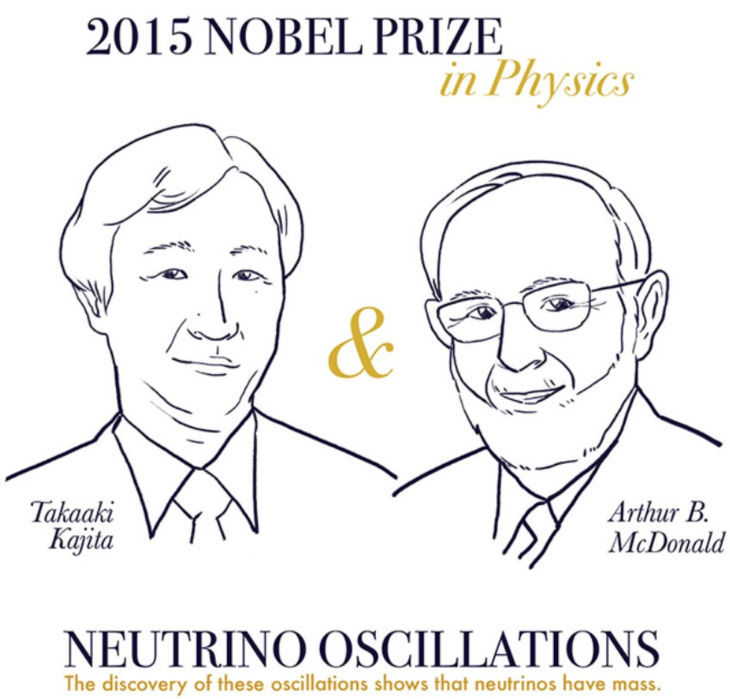


Illustration by Sandbox Studio, Chicago

“Neutrinos, the Standard Model misfits”

Neutrinos – what do we know?



- Neutrinos in the Standard Model are **massless**

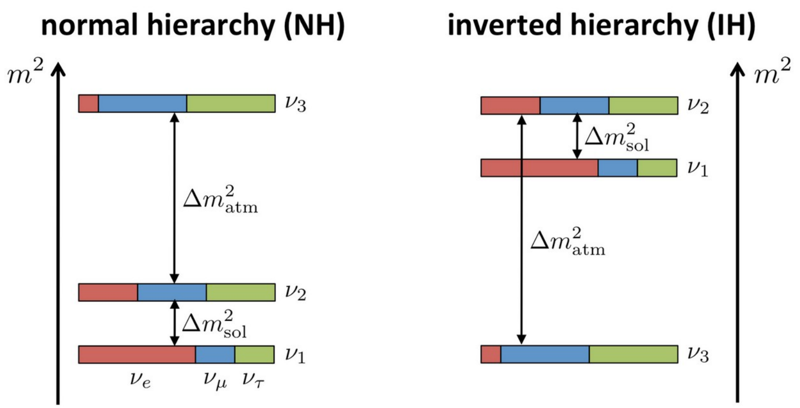
$$L_i \rightarrow \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \qquad m_\nu = 0$$

- Neutrino **mixing**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Neutrino **oscillations** require **massive** neutrinos

$$P(\nu_i \rightarrow \nu_j) \propto \Delta m^2_{ij} \qquad \begin{aligned} \Delta m^2_{12} &\sim 7.59 \times 10^{-5} \mathrm{eV}^2 \\ \Delta m^2_{23} \sim \Delta m^2_{31} &\sim 2.3 \times 10^{-3} \mathrm{eV}^2 \end{aligned}$$



- **Normal** vs. **inverted** hierarchy

How do neutrinos get their masses?
What nature do neutrinos have? Are they their own anti-particles?

Why Lepton-Number Violation?

- Masses of the active neutrinos cannot be explained within the SM
- **BUT** right-handed neutrinos could help

Dirac mass

1/2

$$y_\nu L \epsilon H \nu_R^c \supset m_D \nu_L \nu_R^c$$

-1/2 0

hypercharge

Majorana mass

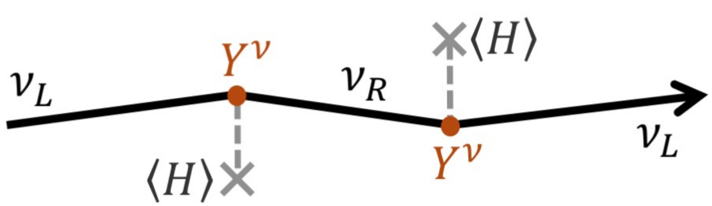
$$m_M \overline{\nu}_R \nu_R^c$$

0 0

- tiny Yukawa couplings

$$m_\nu / \Lambda_{EW} \leq 10^{-12}$$

- Lepton number no accidental symmetry anymore



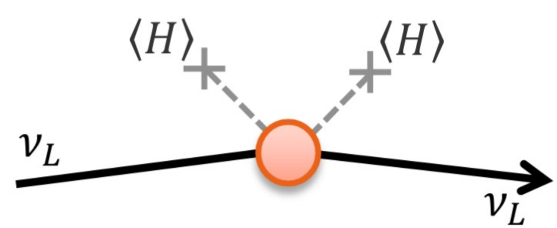
-1/2 1/2

$$m_M \overline{\nu}_L \nu_L^c \qquad LLHH$$

1/2 1/2 -1/2 1/2

not at tree-level within the SM possible

- higher dimensional operator
- Lepton number violation (**LNV**)



Lepton-Number Violation

- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

3/2 3/2 1 1

mass dimension

$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta}\epsilon_{\rho\sigma}$$

$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

$$\mathcal{O}_{8}^{(7)} = L^\alpha \bar{e}^c \bar{u}^c d^c H^\beta \epsilon_{\alpha\beta}$$

$$\mathcal{O}_{14b}^{(9)} = L^\alpha L^\beta \bar{Q}_\alpha \bar{u}^c Q^\rho d^c \epsilon_{\beta\rho}$$

$$\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}$$

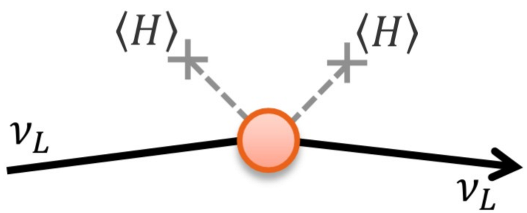
Babu, Leung (2001), de Gouvea, Jenkins (2007), Deppisch, Graf, JH, Huang (2017)

Radiative neutrino mass generation

- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

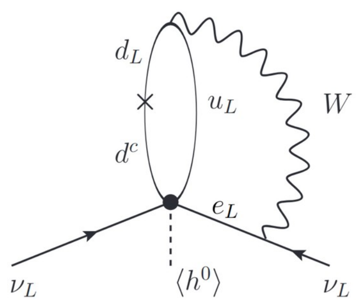
$$\boxed{\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}}$$



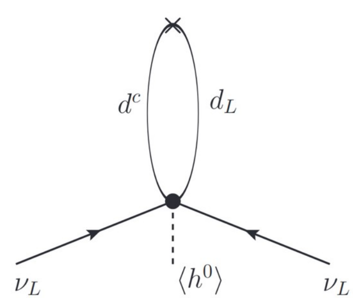
$$m_\nu \approx \frac{v^2}{\Lambda_1}$$

$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta}\epsilon_{\rho\sigma}$$

$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

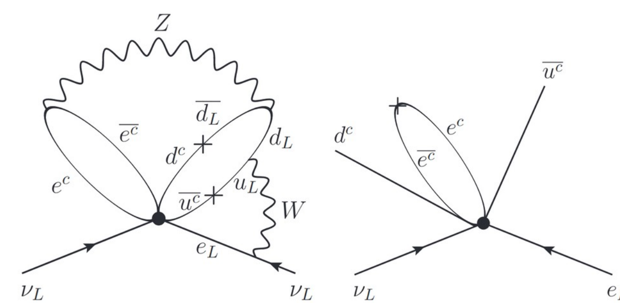


$$m_\nu \approx \frac{y_d g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda_{3a}}$$



$$m_\nu \approx \frac{y_d}{16\pi^2}\frac{v^2}{\Lambda_{3b}}$$

$$\boxed{\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}}$$



$$m_\nu \approx \frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda_{16}}$$

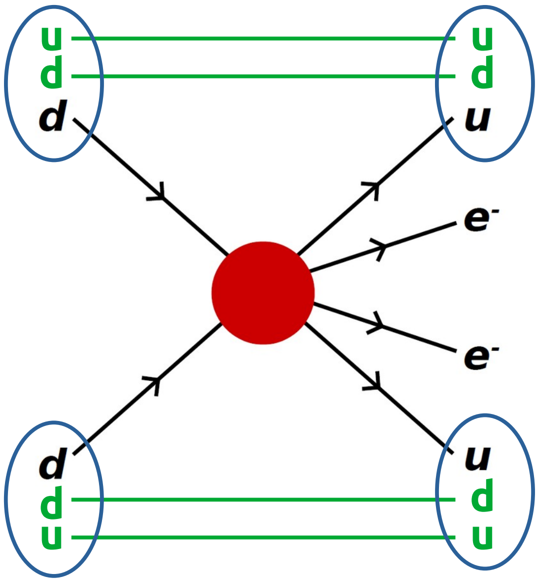
$$L^\alpha = \begin{pmatrix}\nu_L \\ e_L\end{pmatrix}^\alpha, \quad Q^\alpha = \begin{pmatrix}u_L \\ d_L\end{pmatrix}^\alpha, \quad H = \begin{pmatrix}h^+ \\ h^0\end{pmatrix}$$

$$e_\alpha^c, \; u_\alpha^c, \; d_\alpha^c$$

Deppisch, Graf, JH, Huang (2017)

Probing LNV interactions – 0νββ decay

Neutrinoless double beta decay



Most stringent limits are currently set by GERDA and Kamland-Zen:

$$T_{1/2}^{\mathrm{Ge}} \geq 0.9 \times 10^{26}\ \mathrm{y} \qquad T_{1/2}^{\mathrm{Xe}} \geq 1.07 \times 10^{26}\ \mathrm{y}$$

$$\boxed{T_{1/2}^{-1} = \mid m_{\beta\beta} \mid^2 G^{0\nu} \mid M^{0\nu} \mid^2}$$

particle physics

phase space factor

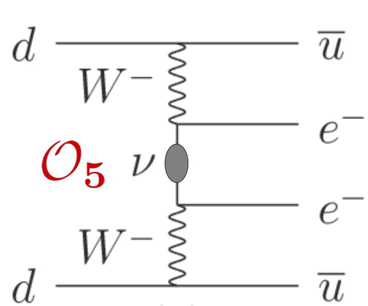
nuclear matrix element

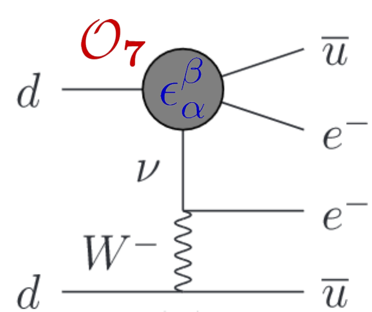
standard mass mechanism

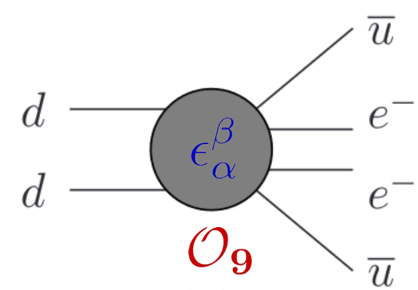
long range contribution

short range contribution

?
=

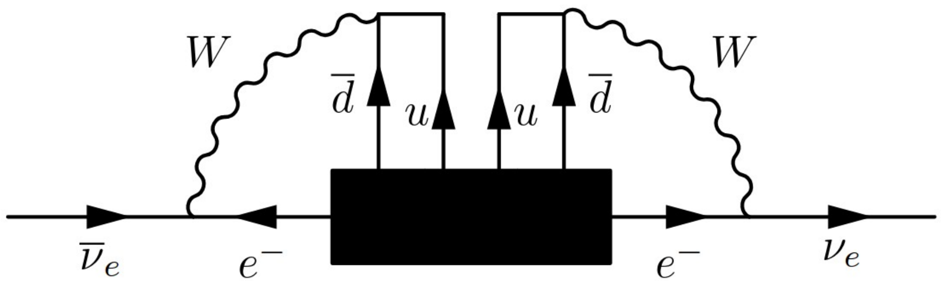






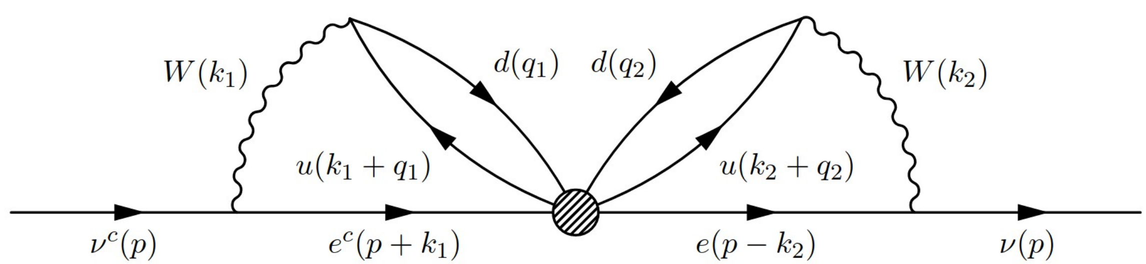
0νββ decay probes only first generation!

Schechter-Valle Theorem – Black Box Theorem



Schechter, Valle (1982)

Any ΔL = 2 operator that leads to 0vbb will induce a **Majorana mass contribution** via loop



Dürr, Merle, Lindner (2011)

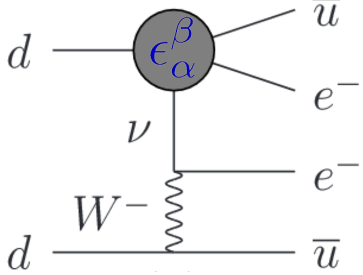
9-dim ΔL = 2 operator will lead to 0vbb but only **tiny contribution** to neutrino mass

$$\delta m_\nu = 10^{-28}\mathrm{eV}$$

Observation of 0vββ decay does not imply that the mass mechanism is the dominant contribution.

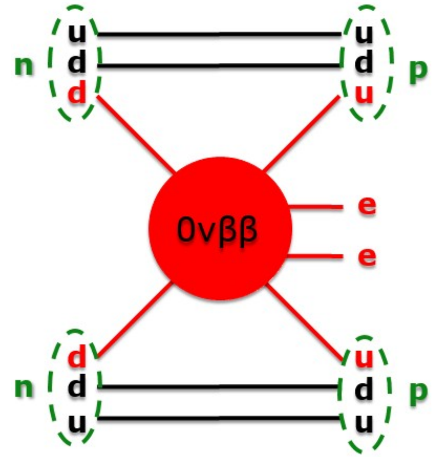
Constraining LNV interactions

long range contribution



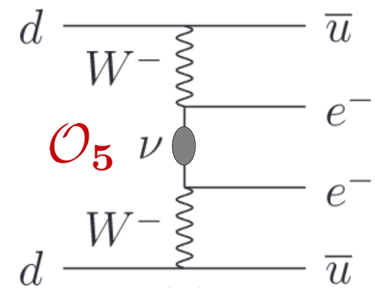
$\mathcal{O}_7$

$\stackrel{?}{=}$



$\stackrel{?}{=}$

standard mass mechanism



$$\boxed{T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2}$$

$$\boxed{T_{1/2}^{-1} = G_{0\nu} \mid \mathcal{M} \mid^2 \mid m_{\beta\beta} \mid^2}$$

Leptonic and hadronic current with different chirality structure:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\{j^\mu_{V-A}J^\dagger_{V-A,\mu} + \sum_{\alpha,\beta}\epsilon_\alpha^\beta j_\beta J_\alpha^\dagger\}$$

$$j_\beta = \bar{e}\mathcal{O}_\beta\nu$$

$$J_\alpha^\dagger = \bar{u}\mathcal{O}_\alpha d$$

$$\mathcal{O}_{V\pm A} = \gamma^\mu(1\pm\gamma_5)$$

$$\mathcal{O}_{S\pm P} = (1\pm\gamma_5)$$

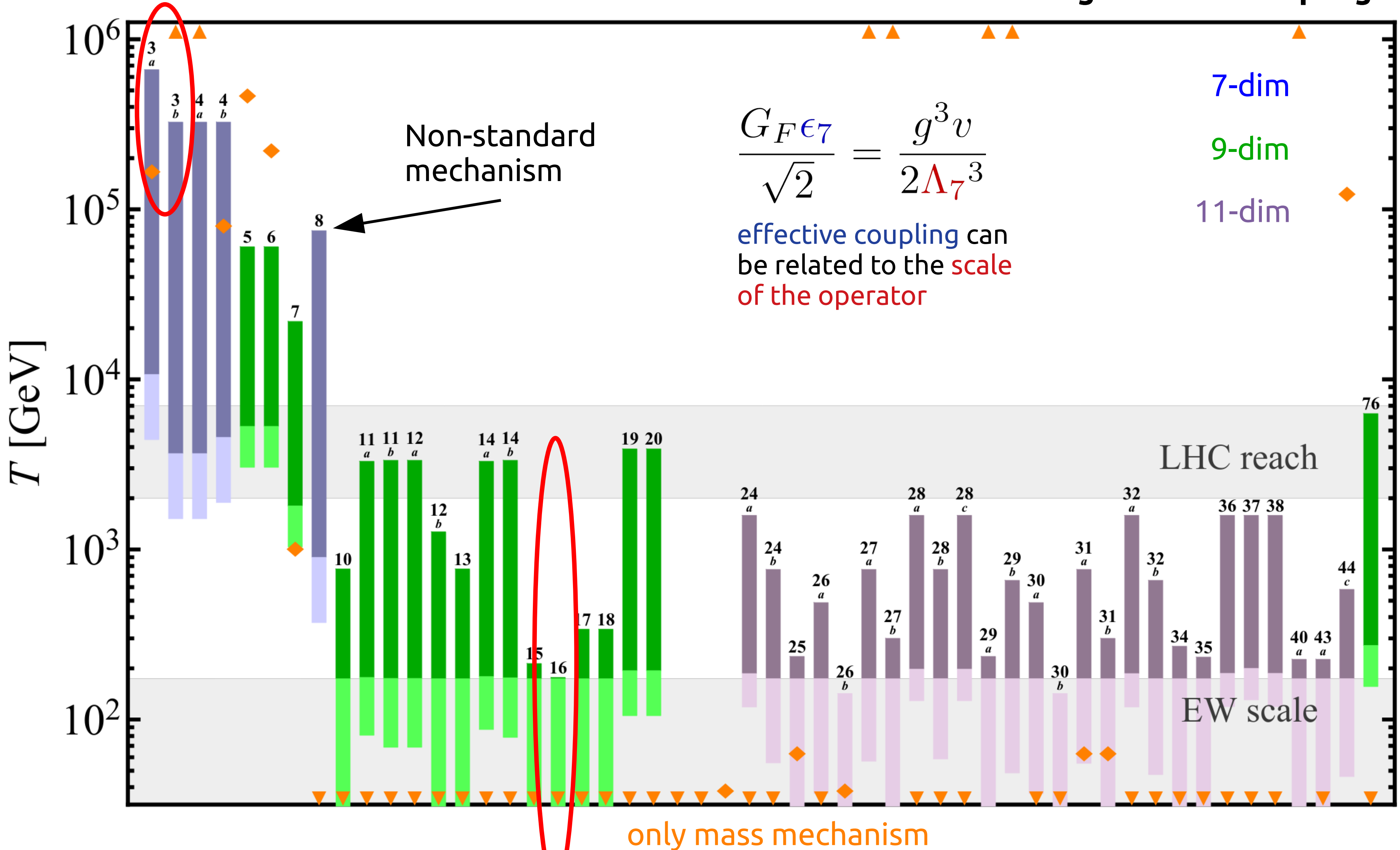
$$\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_\mu,\gamma_\nu](1\pm\gamma_5)$$

$\lvert\epsilon\rvert \times 10^8$	ϵ_ν	ϵ^{V+A}_{V-A}	ϵ^{V+A}_{V+A}	$\epsilon^{S+P}_{S\pm P}$	$\epsilon^{T_R}_{T_R}$
^{76}Ge	41	0.21	37	0.66	0.07
^{76}Xe	26	0.11	22	0.26	0.03

Deppisch, Hirsch, Päs (2012)

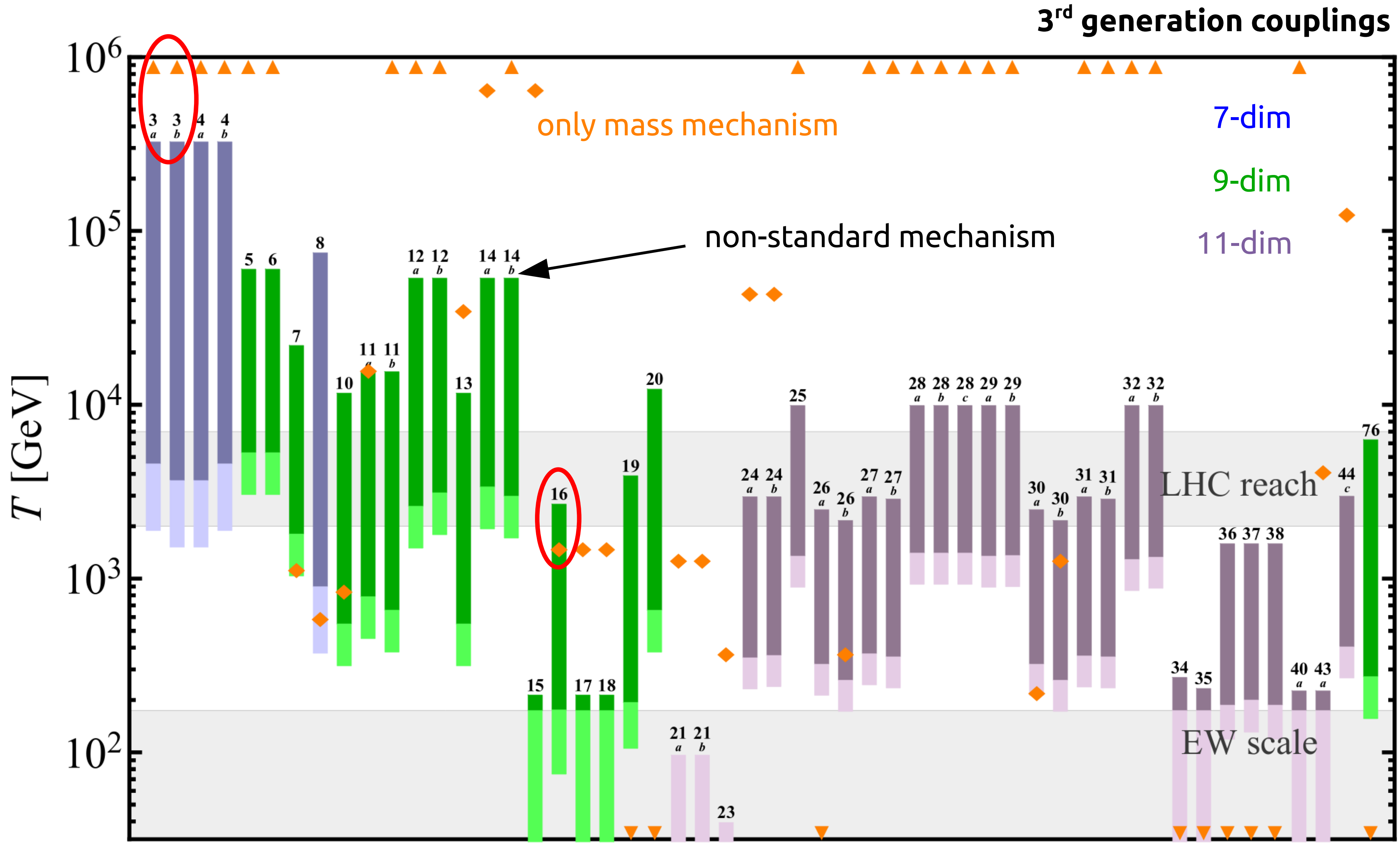
Scales of New Physics

1st generation couplings



Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Scales of New Physics



Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Uncertainties of Nuclear Matrix Elements

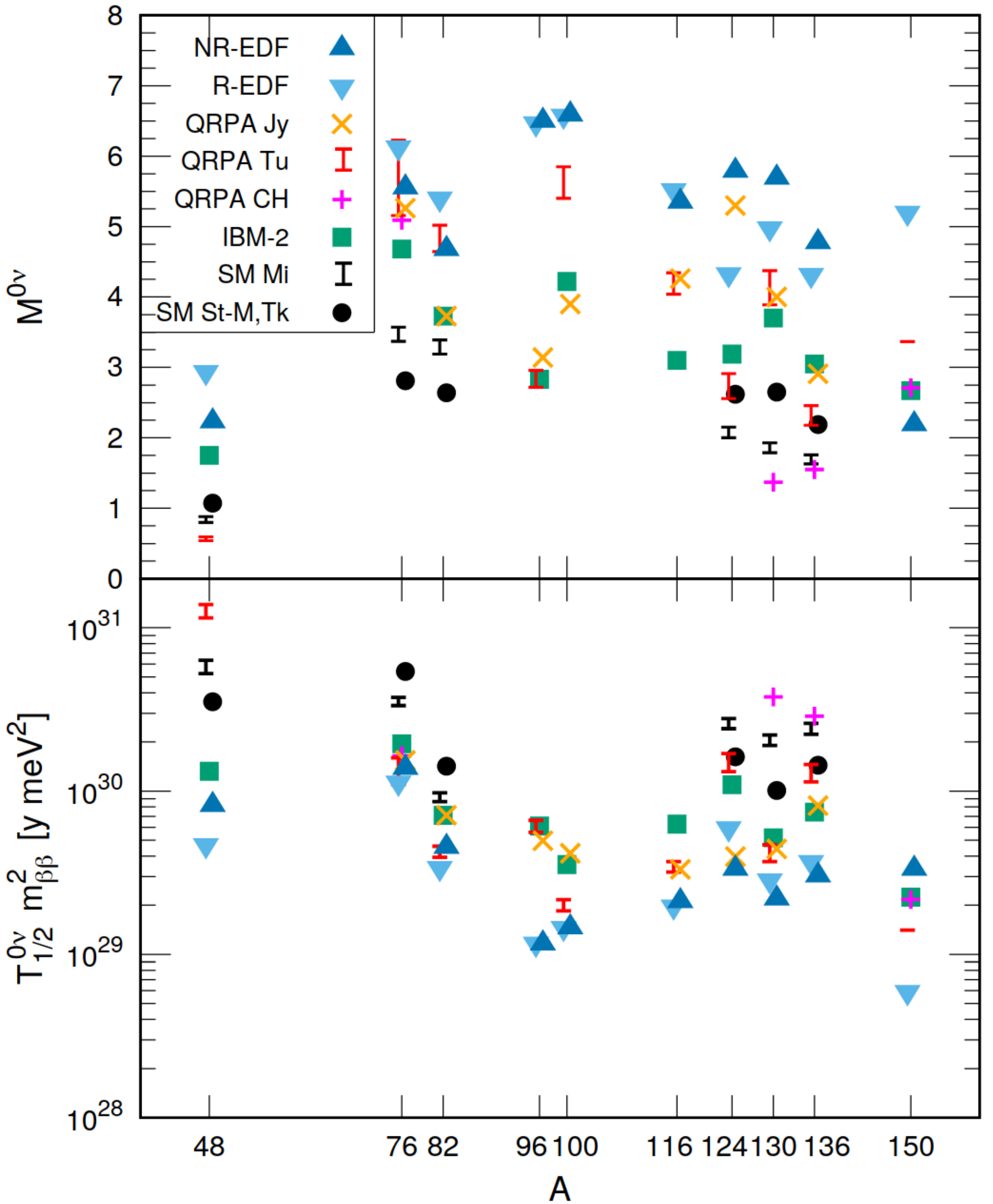
$$T_{1/2}^{-1} = | m_{\beta\beta} |^2 \, G^{0\nu} \, | M^{0\nu} |^2$$

nuclear physics

- **Dependence** on isotope and specific operator
- Differences between different **nuclear models**
- "**the g_A problem**" quenching of the axial-vector coupling?

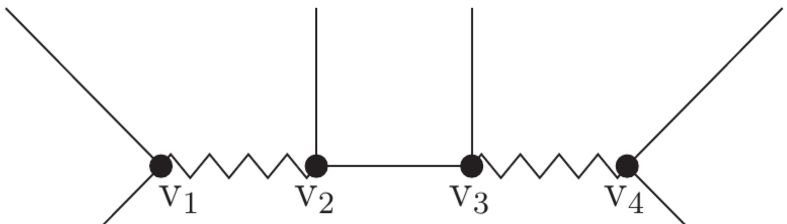
$$\mathcal{M} = \mathcal{M}_{GT} - \frac{g_V^2}{g_A^2}\mathcal{M}_F + \mathcal{M}_T$$

e.g. Suhonen et al., Engel et al., and many more

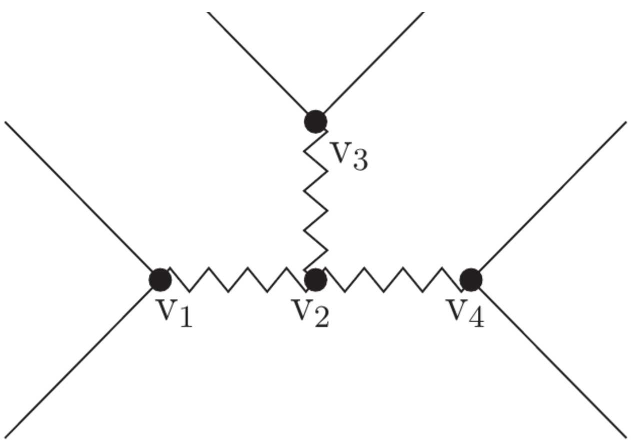


Engel, Menendez (2016)

Topologies for Neutrinoless Double Beta Decay



Topology I

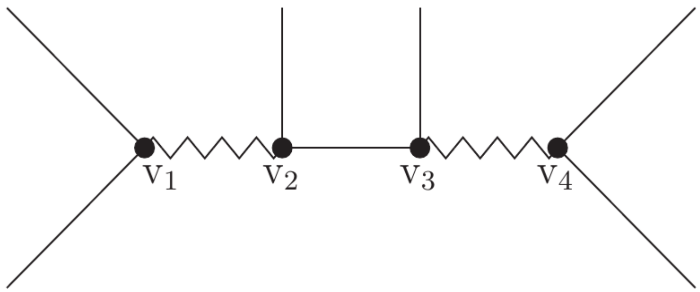


Topology II

#	Decomposition	Long Range?	Mediator $(U(1)_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58-60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62,63]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60], LQ [65,66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58-60], LQ [65,66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58-60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58-60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

Bonnet, Hirsch, Ota, Winter (2014)

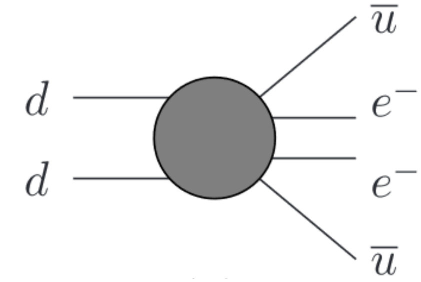
Neutrinoless Double Beta Decay at the LHC



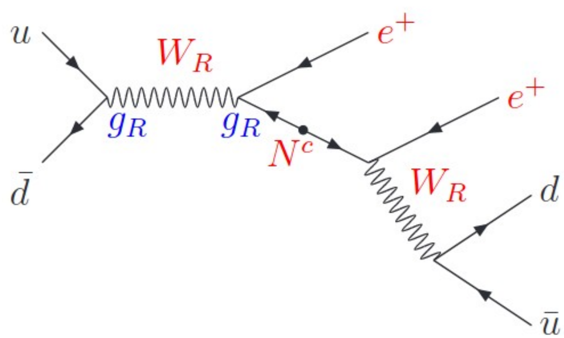
Topology I

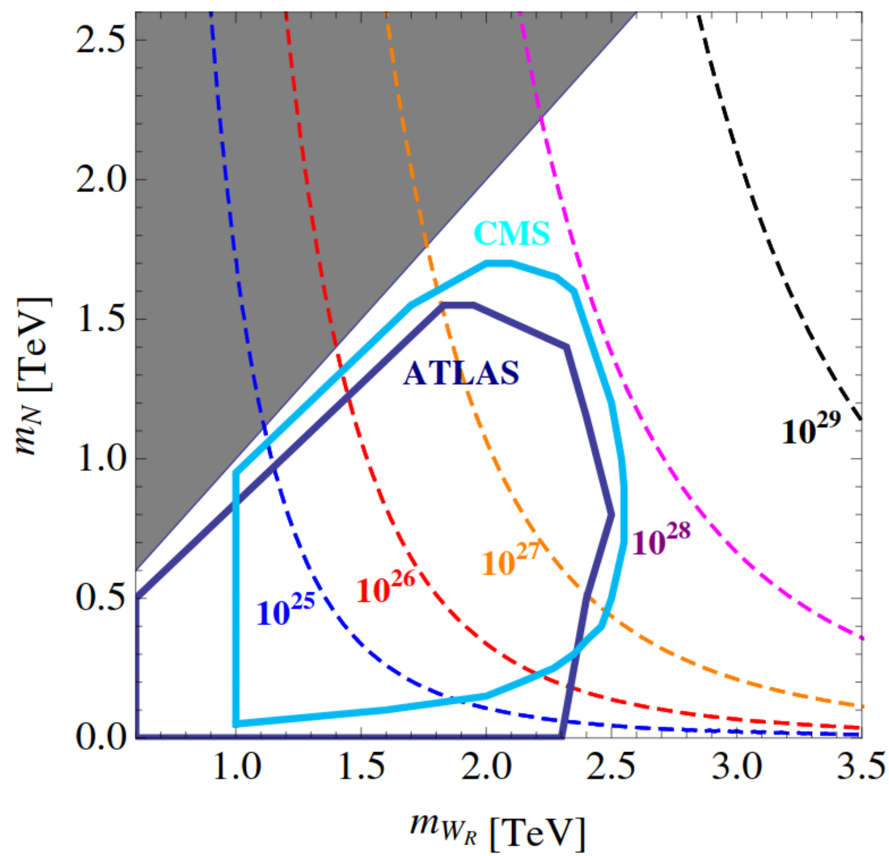
$$\mathcal{O}_9 = \frac{c_9}{\Lambda^5}\bar{u}\bar{u}\bar{d}\bar{d}\bar{e}\bar{e}$$

$$\Lambda \geq (1.2-3.2)\, g_{\mathrm{eff}}^{4/5}\,\mathrm{TeV}$$



Example: Left-Right Symmetric Model

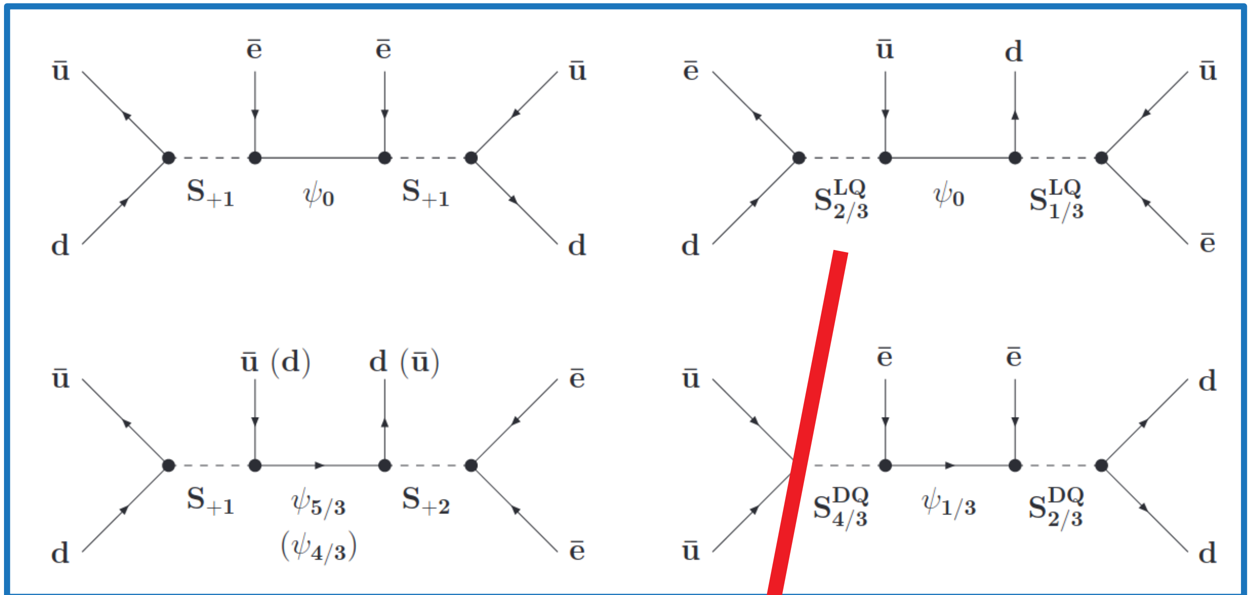


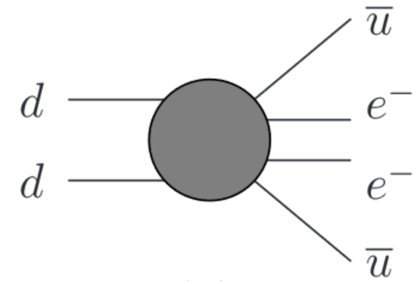


Helo, Kovalenko, Hirsch, Päs (2013)

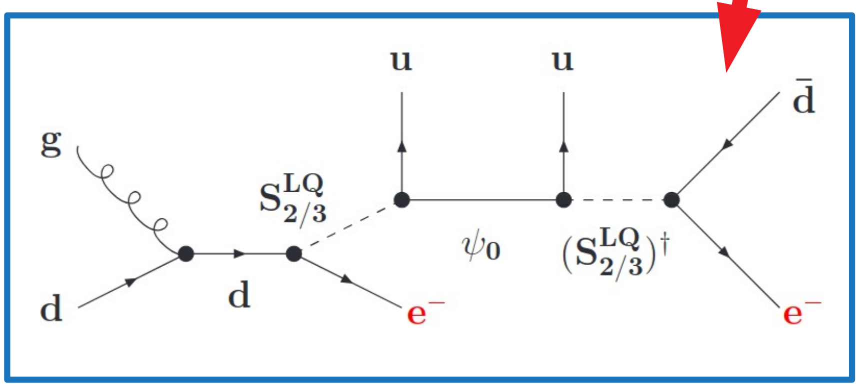
Neutrinoless Double Beta Decay at the LHC

Different possible contributions to 0vbb:





Corresponding process at LHC:



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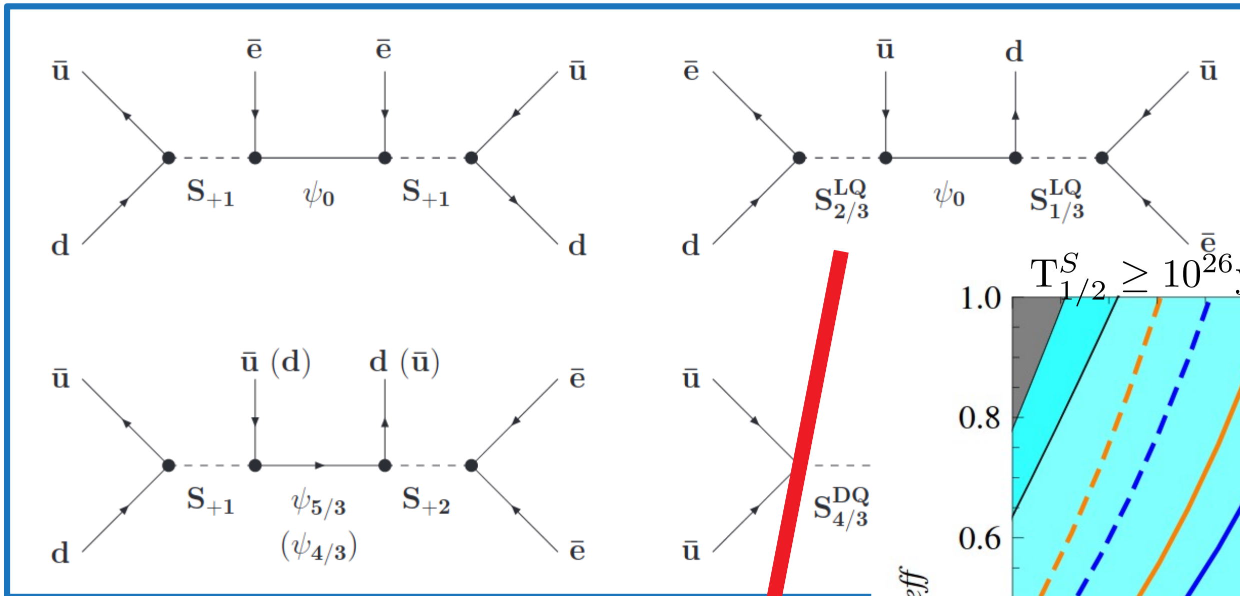
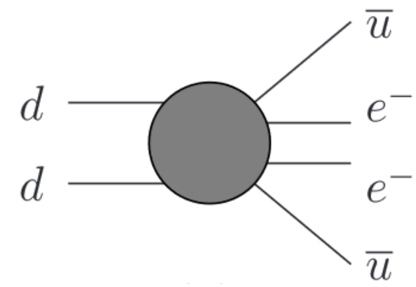
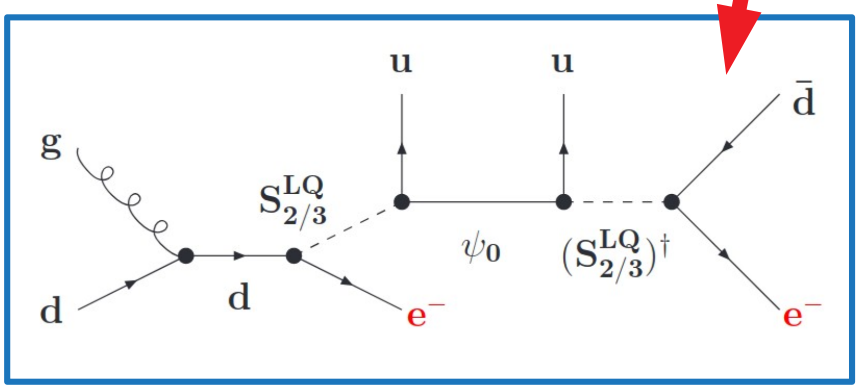
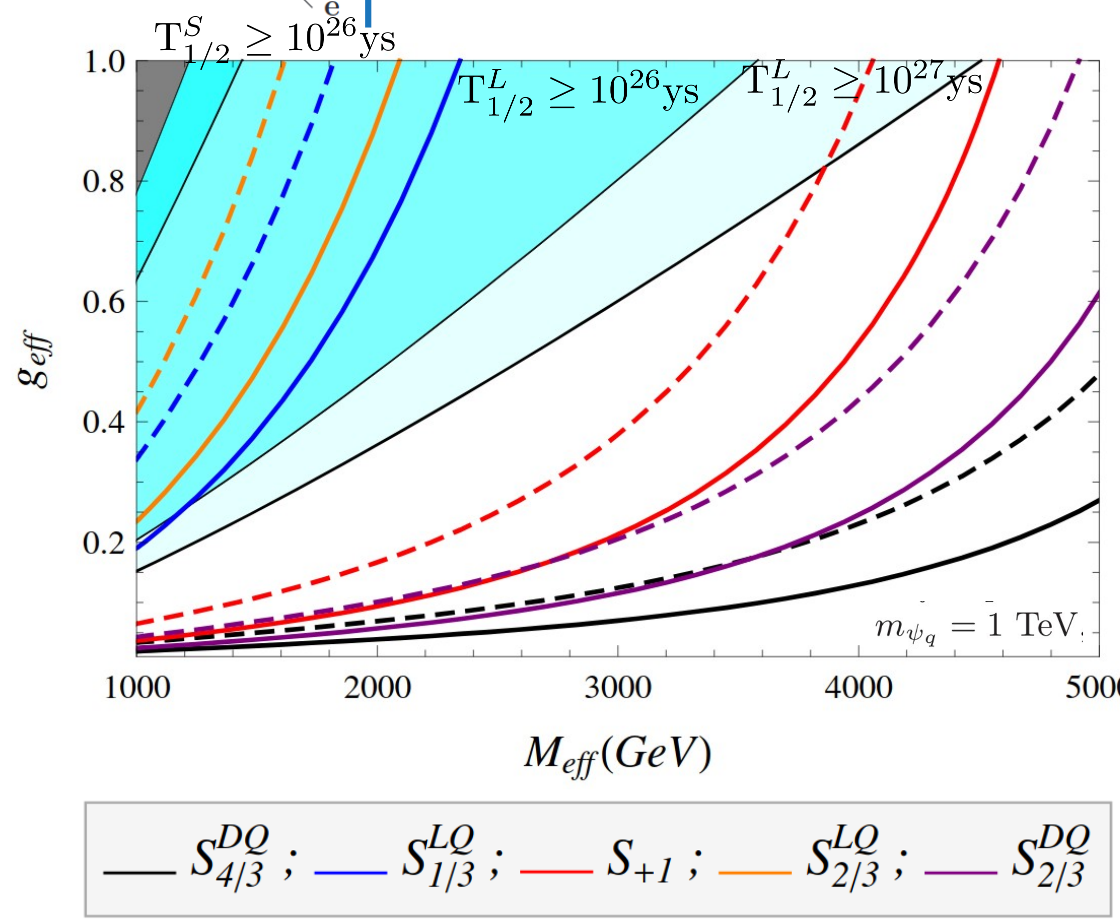




Corresponding process at LHC:



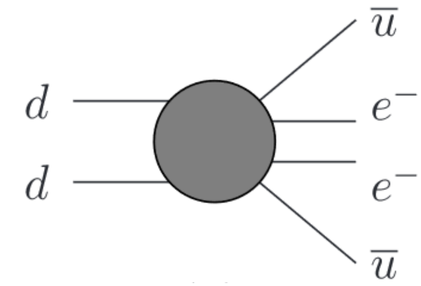


Helo, Kovalenko, Hirsch, Päs (2013)

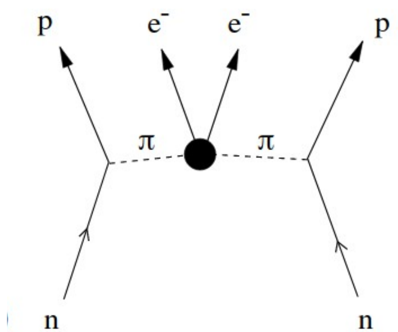
Neutrinoless Double Beta Decay at the LHC

Refined study of one model:

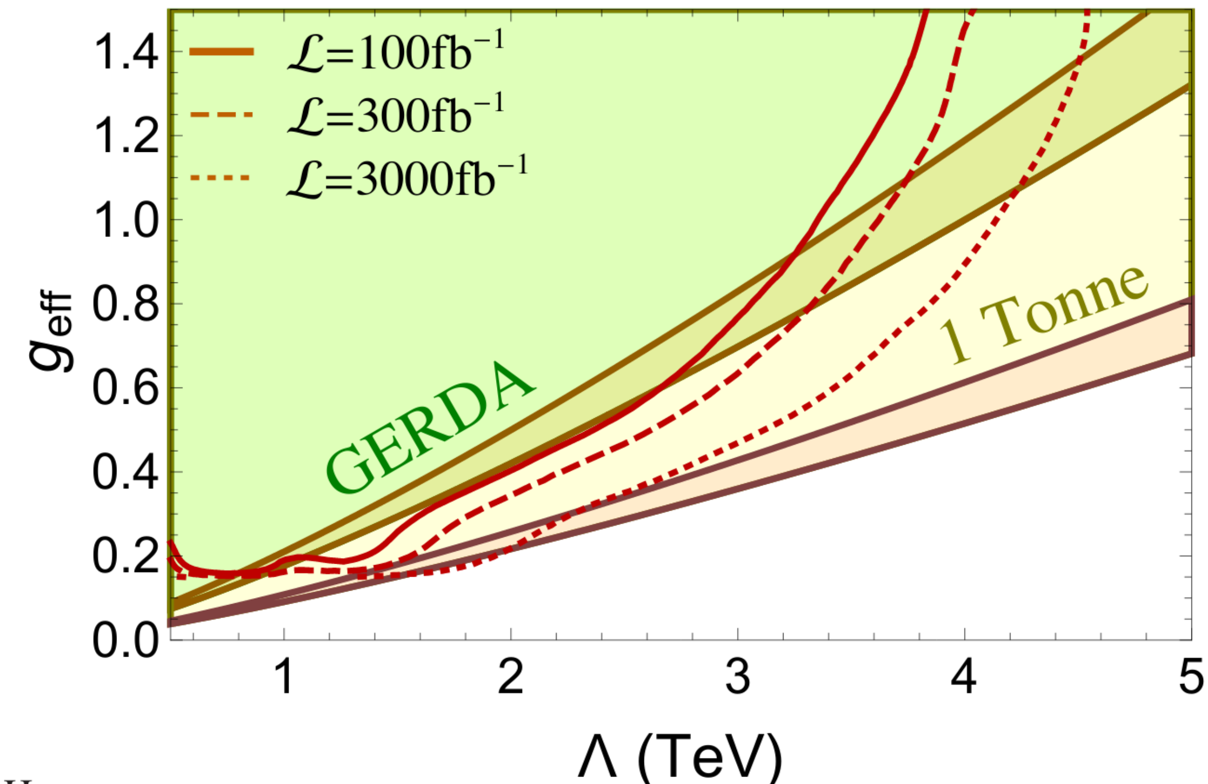
$$\mathcal{L}_{\rm INT} = g_1 \bar{Q}_i^{\alpha} d^{\alpha} S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$



Including:
- SM + detector background
- running of the operators
- long distance contributions



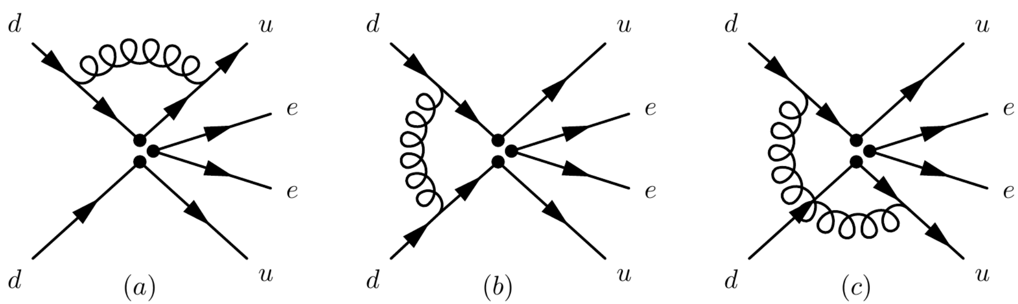
$$\frac{C_{\rm eff}}{\Lambda} \mathcal{O}_{2+}^{++} \bar{e}_L e_R^c + \text{H.c.} \rightarrow \frac{C_{\rm eff} \Lambda_H^2 F_\pi^2}{2\Lambda^5} \pi^- \pi^- \bar{e}_L e_R^c + \text{H.c.},$$



Peng, Ramsey-Musolf, Winslow (2015)

QCD corrections and running

Leading order QCD corrections to the **complete set of the short-range** d = 9 0νββ-operators covering the low-energy limits of any possible underlying high-energy scale model



$$
\begin{aligned}
\mathcal{O}_1^{XY} &= 4(\bar{u}P_X d)(\bar{u}P_Y d)\; j,\\
\mathcal{O}_2^{XX} &= 4(\bar{u}\sigma^{\mu\nu}P_X d)(\bar{u}\sigma_{\mu\nu}P_X d)\; j,\\
\mathcal{O}_3^{XY} &= 4(\bar{u}\gamma^{\mu}P_X d)(\bar{u}\gamma_{\mu}P_Y d)\; j,\\
\mathcal{O}_4^{XY} &= 4(\bar{u}\gamma^{\mu}P_X d)(\bar{u}\sigma_{\mu\nu}P_Y d)\; j^{\nu},\\
\mathcal{O}_5^{XY} &= 4(\bar{u}\gamma^{\mu}P_X d)(\bar{u}P_Y d)\; j_{\mu}
\end{aligned}
$$

$$
\boxed{
\begin{aligned}
\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \; & G_1 \Big| \beta_1^{XX}\left(C_1^{LL}(\Lambda) + C_1^{RR}(\Lambda)\right) + \beta_1^{LR}\left(C_1^{LR}(\Lambda) + C_1^{RL}(\Lambda)\right) + \\
& \quad + \beta_2^{XX}\left(C_2^{LL}(\Lambda) + C_2^{RR}(\Lambda)\right) + \\
& \quad + \beta_3^{XX}\left(C_3^{LL}(\Lambda) + C_3^{RR}(\Lambda)\right) + \beta_3^{LR}\left(C_3^{LR}(\Lambda) + C_3^{RL}(\Lambda)\right)\Big|^2 + \\
& + G_2 \Big| \beta_4^{XX}\left(C_4^{RR}(\Lambda) + C_4^{RR}(\Lambda)\right) + \beta_4^{LR}\left(C_4^{LR}(\Lambda) + C_4^{RL}(\Lambda)\right) + \\
& \quad + \beta_5^{XX}\left(C_5^{RR}(\Lambda) + C_5^{RR}(\Lambda)\right) + \beta_5^{LR}\left(C_5^{LR}(\Lambda) + C_5^{RL}(\Lambda)\right)\Big|^2 ,
\end{aligned}
}
$$

e.g.

$$
\beta_1^{XX} = \mathcal{M}_1 \; U_{(12)11}^{XX} + \mathcal{M}_2 U_{(12)21}^{XX},
$$

Gonzalez, Hirsch, Kovalenko (2015)

QCD corrections and running

- QCD corrections can give **sizeable impact** to **short range** contribution

	With QCD		Without QCD	With QCD		Without QCD
^{A}X	$\lvert C_1^{XX}(\Lambda_1)\rvert$	$\lvert C_1^{XX}(\Lambda_2)\rvert$	$\lvert C_1^{XX}\rvert$	$\lvert C_1^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_1^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_1^{LR,RL}\rvert$
^{76}Ge	5.0×10^{-10}	3.8×10^{-10}	$\mathbf{2.6 \times 10^{-7}}$	1.5×10^{-8}	9.1×10^{-9}	$\mathbf{2.6 \times 10^{-7}}$
^{136}Xe	3.4×10^{-10}	2.6×10^{-10}	$\mathbf{1.8 \times 10^{-7}}$	9.7×10^{-9}	6.1×10^{-9}	$\mathbf{1.8 \times 10^{-7}}$
^{A}X	$\lvert C_2^{XX}(\Lambda_1)\rvert$	$\lvert C_2^{XX}(\Lambda_2)\rvert$	$\lvert C_2^{XX}\rvert$	–	–	–
^{76}Ge	3.5×10^{-9}	5.2×10^{-9}	1.4×10^{-9}	–	–	–
^{136}Xe	2.4×10^{-9}	3.5×10^{-9}	9.4×10^{-10}	–	–	–
^{A}X	$\lvert C_3^{XX}(\Lambda_1)\rvert$	$\lvert C_3^{XX}(\Lambda_2)\rvert$	$\lvert C_3^{XX}\rvert$	$\lvert C_3^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_3^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_3^{LR,RL}\rvert$
^{76}Ge	1.5×10^{-8}	1.6×10^{-8}	1.1×10^{-8}	2.0×10^{-8}	2.1×10^{-8}	1.8×10^{-8}
^{136}Xe	9.7×10^{-9}	1.1×10^{-8}	7.4×10^{-9}	1.4×10^{-8}	1.4×10^{-8}	1.2×10^{-8}
^{A}X	$\lvert C_4^{XX}(\Lambda_1)\rvert$	$\lvert C_4^{XX}(\Lambda_2)\rvert$	$\lvert C_4^{XX(0)}\rvert$	$\lvert C_4^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_4^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_4^{LR,RL(0)}\rvert$
^{76}Ge	5.0×10^{-9}	3.9×10^{-9}	$\mathbf{1.2 \times 10^{-8}}$	1.7×10^{-8}	1.9×10^{-8}	1.2×10^{-8}
^{136}Xe	3.4×10^{-9}	2.7×10^{-9}	$\mathbf{7.9 \times 10^{-9}}$	1.2×10^{-8}	1.3×10^{-8}	7.9×10^{-9}
^{A}X	$\lvert C_5^{XX}(\Lambda_1)\rvert$	$\lvert C_5^{XX}(\Lambda_2)\rvert$	$\lvert C_5^{XX}\rvert$	$\lvert C_5^{LR,RL}(\Lambda_1)\rvert$	$\lvert C_5^{LR,RL}(\Lambda_2)\rvert$	$\lvert C_5^{LR,RL}\rvert$
^{76}Ge	2.3×10^{-8}	1.4×10^{-8}	$\mathbf{1.2 \times 10^{-7}}$	3.9×10^{-8}	2.8×10^{-8}	$\mathbf{1.2 \times 10^{-7}}$
^{136}Xe	1.6×10^{-8}	9.5×10^{-9}	$\mathbf{8.2 \times 10^{-8}}$	2.8×10^{-8}	2.0×10^{-8}	$\mathbf{8.2 \times 10^{-8}}$

Gonzalez, Hirsch, Kovalenko (2015)

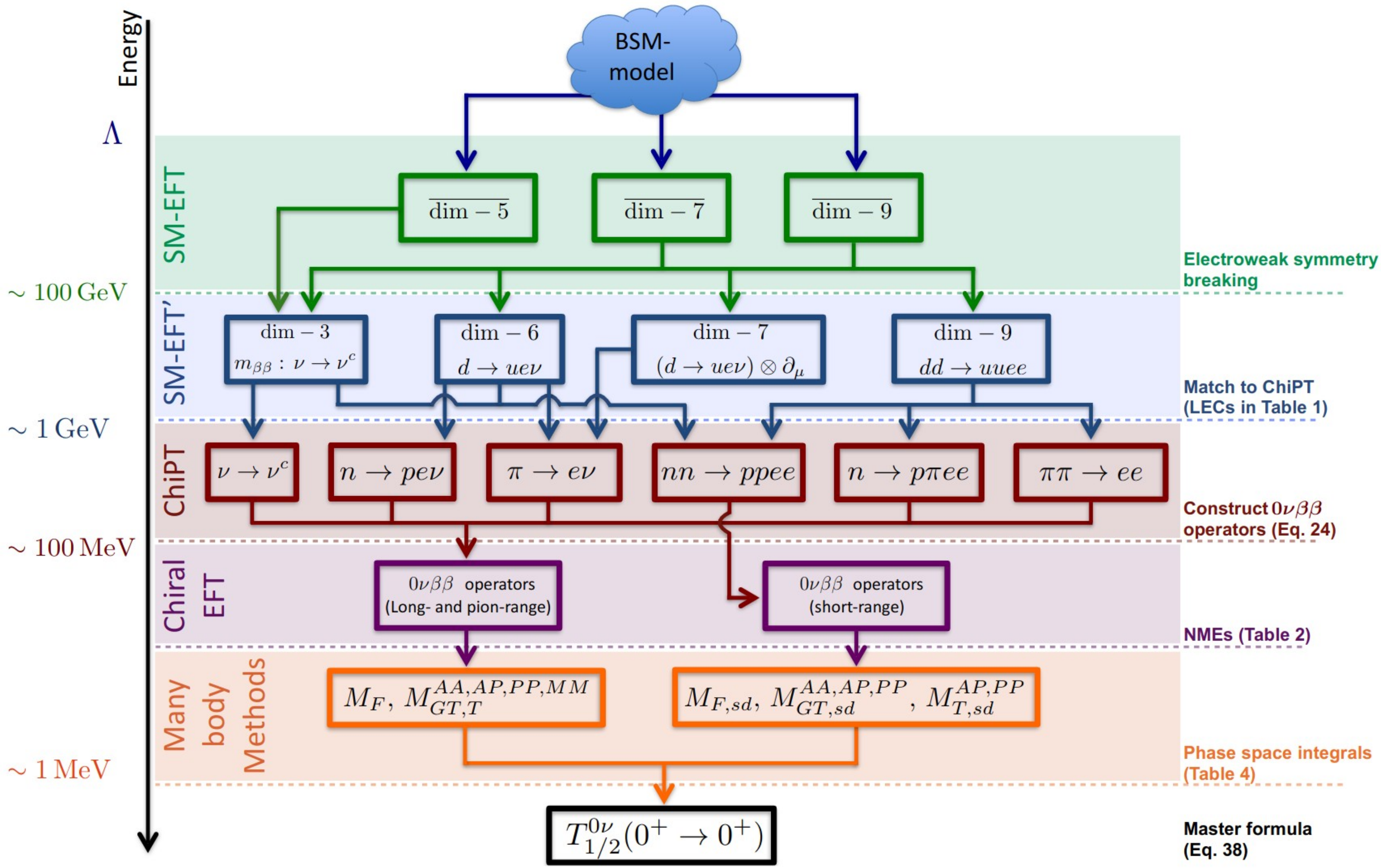
- QCD corrections **sub-dominant** for **long range** contribution (less than 60%)

Arbelaez, Gonzalez, Hirsch, Kovalenko (2016)

- Extrapolation of perturbative results to sub-GeV non-perturbative scales on the basis of **QCD coupling constant “freezing” behavior** using Background Perturbation Theory
  → only **moderate** dependence

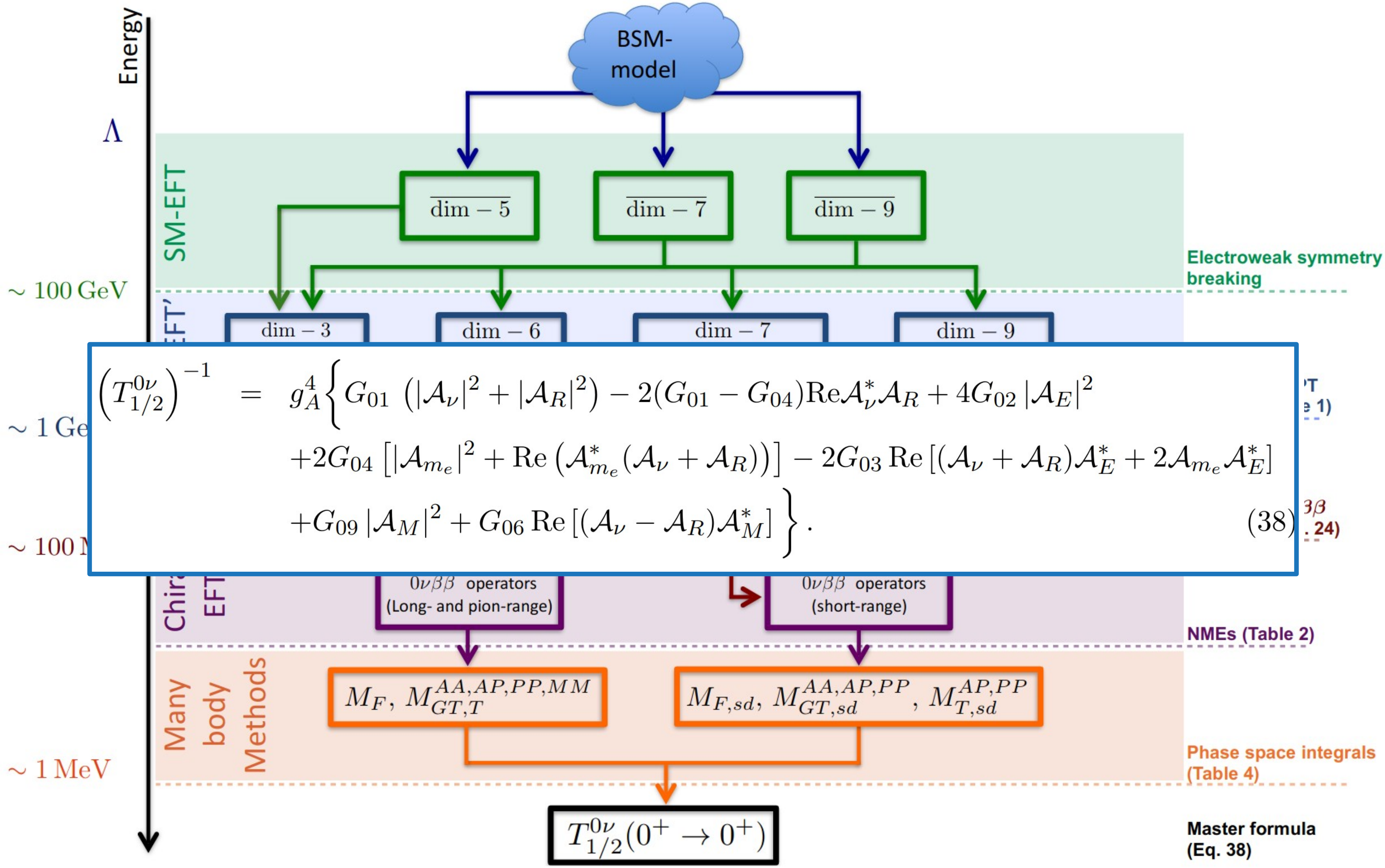
Gonzalez, Hirsch, Kovalenko (2018)

“Master formula”



Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2017, 2018)
Graf, Deppisch, Iachello, Kotila (2018)

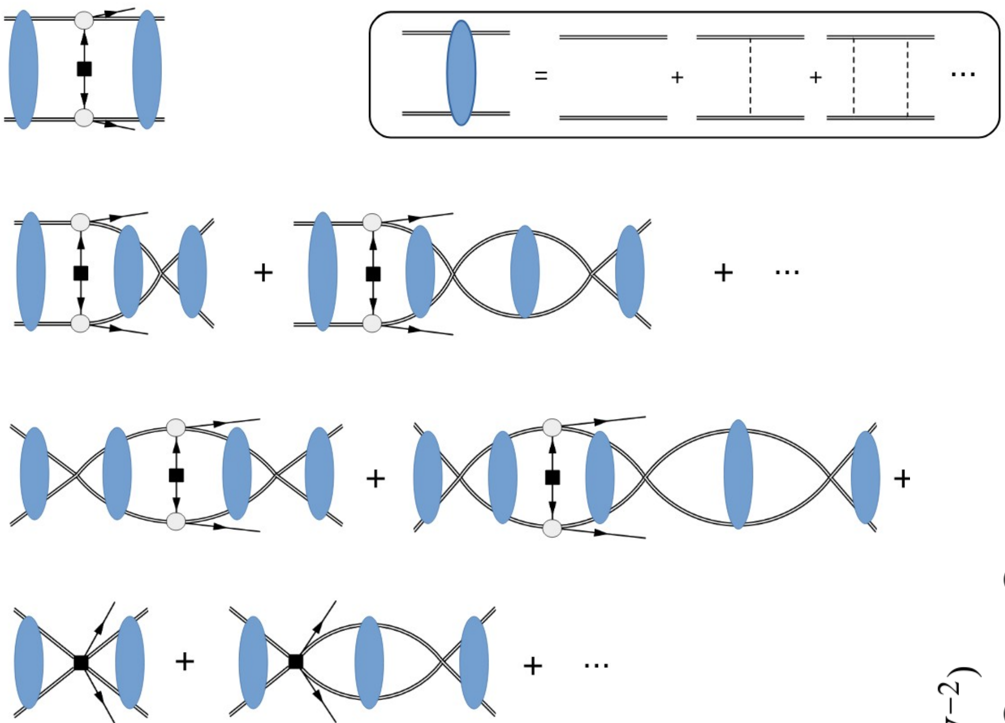
“Master formula”



$$
\begin{aligned}
\left(T_{1/2}^{0\nu}\right)^{-1} \quad = \quad & g_A^4 \Big\{ G_{01}\ \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04})\mathrm{Re}\mathcal{A}_\nu^* \mathcal{A}_R + 4G_{02}\,|\mathcal{A}_E|^2 \\
& + 2G_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu + \mathcal{A}_R)\right)\right] - 2G_{03}\,\mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right] \\
& + G_{09}\,|\mathcal{A}_M|^2 + G_{06}\,\mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R)\mathcal{A}_M^*\right] \Big\}\,. \qquad (38)
\end{aligned}
$$

Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2017, 2018)
Graf, Deppisch, Iachello, Kotila (2018)

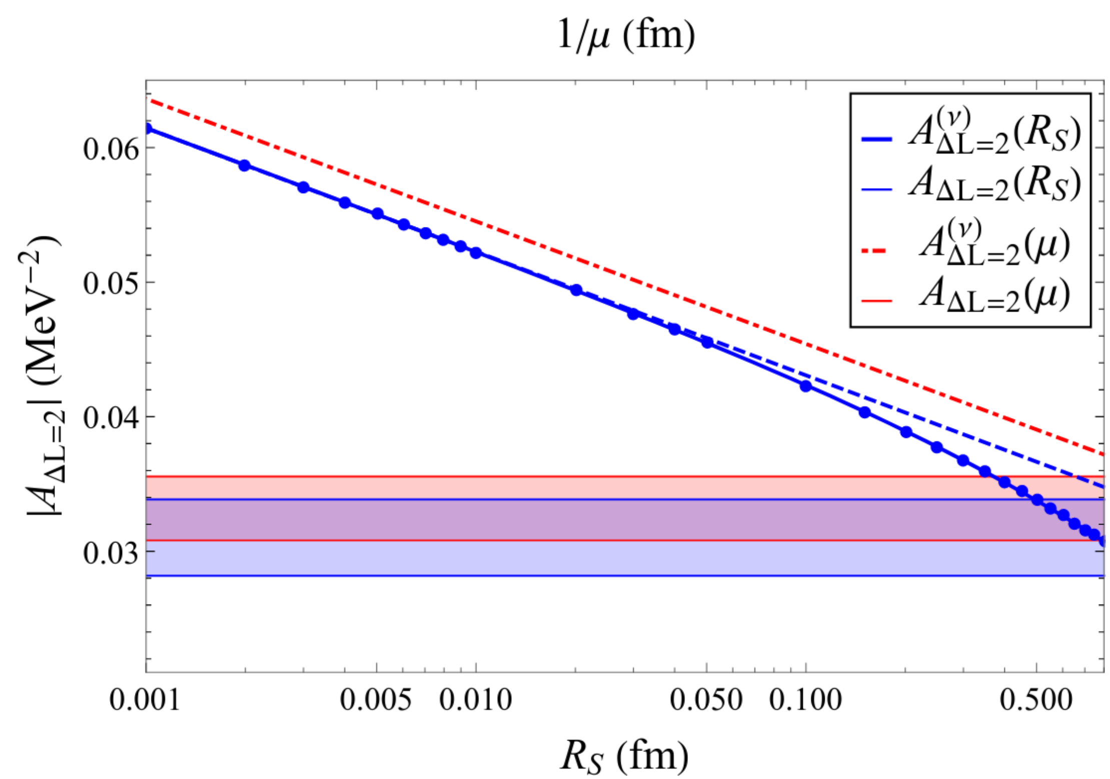
A new leading contribution to 0νββ



$$H_{\rm LNV} = 2 G_F^2 V_{ud}^2 \; m_{\beta\beta} \; \bar{e}_L C \bar{e}_L^T \; V_\nu$$

$$V_0(\mathbf{q}) = \tilde{C} + V_\pi(\mathbf{q})\,, \quad V_\pi(\mathbf{q}) = -\frac{g_A^2}{4F_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

$$\boxed{V_{\nu,CT} = -2 g_\nu^{NN} \; \tau^{(1)+}\tau^{(2)+}}$$



Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck (2018)

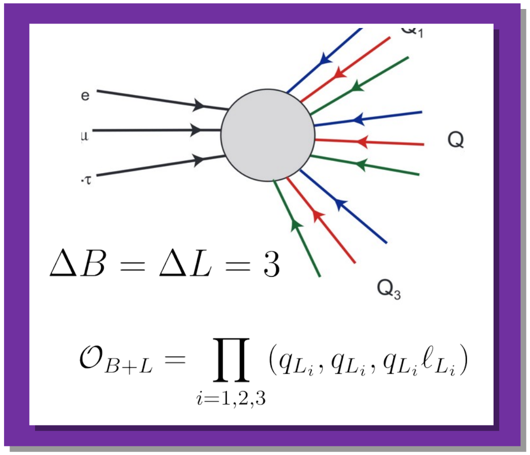
Implications on Leptogenesis

- generation of lepton asymmetry via heavy neutrino decays
- competition with lepton number violating (LNV) washout processes
- conversion to baryon asymmetry via sphaleron processes

Fukugita et al. 1986

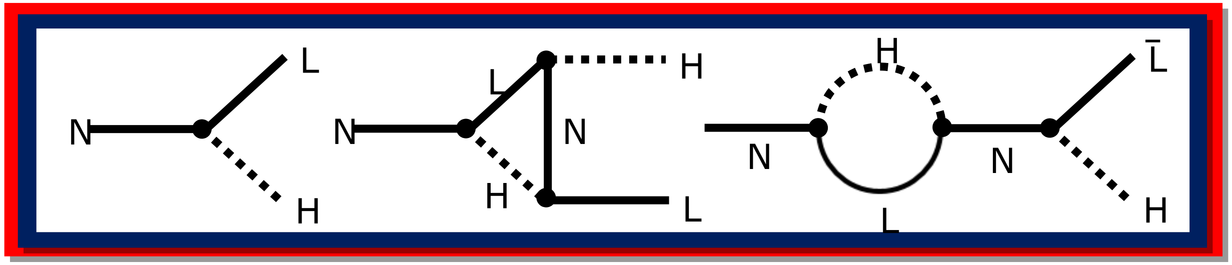
$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\mathrm{eq}})$$

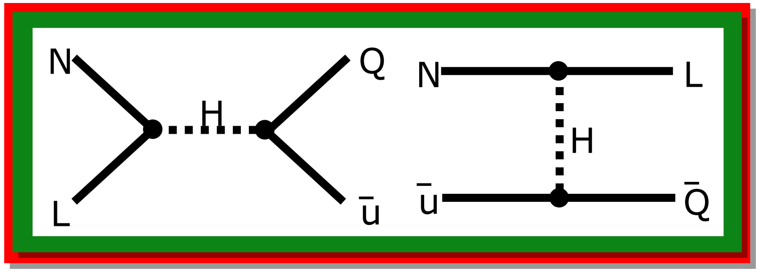
$$Hz\frac{dN_L}{dz} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{\mathrm{eq}}) - \Gamma_W N_L$$



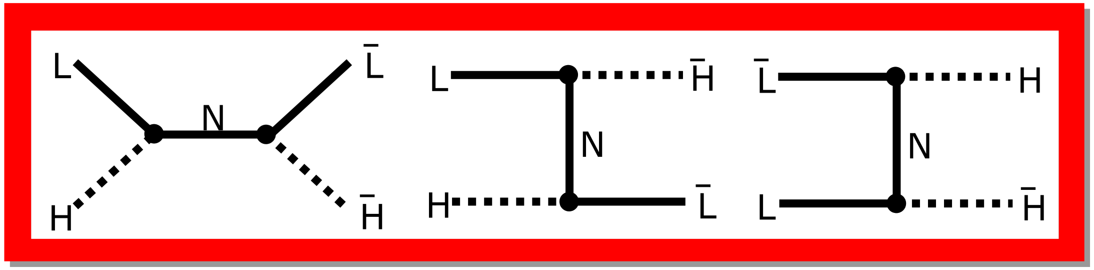
sphaleron processes

$\Delta L = 1$ source of CP violation





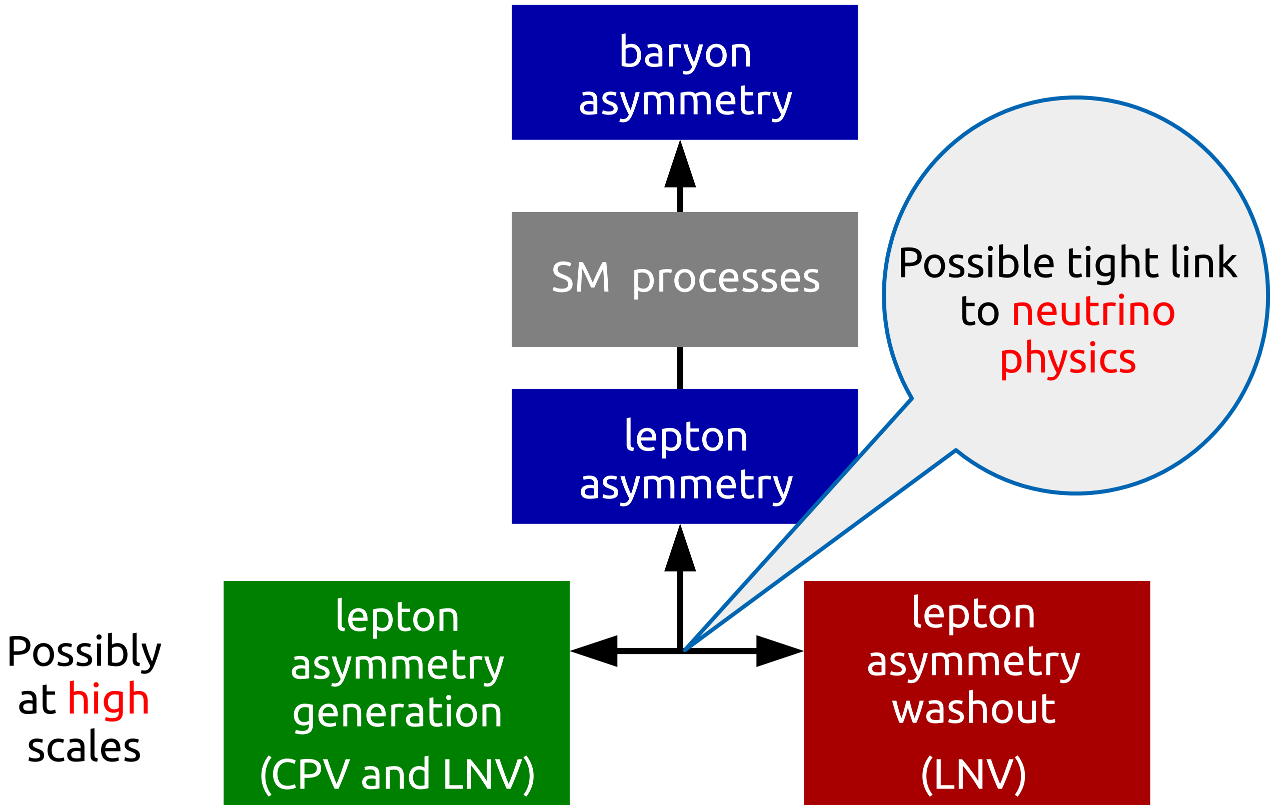
$\Delta L = 1$ scattering processes



$\Delta L = 2$ washout processes

Implications on Leptogenesis

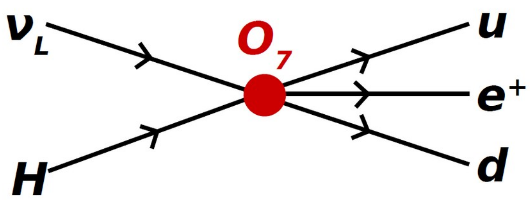
The generation of a baryon asymmetry – baryogenesis – can be created by a lepton asymmetry – leptogenesis:



In turn, lepton number violation (LNV) can destroy a lepton asymmetry, and thus even a baryon asymmetry!

Lepton Asymmetry Washout

- LNV operator would cause washout of **pre-existing** net lepton asymmetry in the early Universe



$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c})H^j \epsilon_{ij}$$

$$zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} = -\left(\frac{n_{L_e} n_{\bar{e^c}}}{n_{L_e}^{\text{eq}} n_{\bar{e^c}}^{\text{eq}}} - \frac{n_{u^c} n_{\bar{d^c}} n_{\bar{H}}}{n_{u^c}^{\text{eq}} n_{\bar{d^c}}^{\text{eq}} n_{\bar{H}}^{\text{eq}}}\right) \gamma^{\text{eq}}(L_e \bar{e^c} \to u^c \bar{d^c} \bar{H})$$

$$zHn_\gamma \frac{d\eta_{\Delta L_e}}{dz} = -c_D \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}} \eta_{\Delta L_e}$$

$$\gamma^{eq} \propto \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}}$$

c_D operator specific factor

η_L lepton density

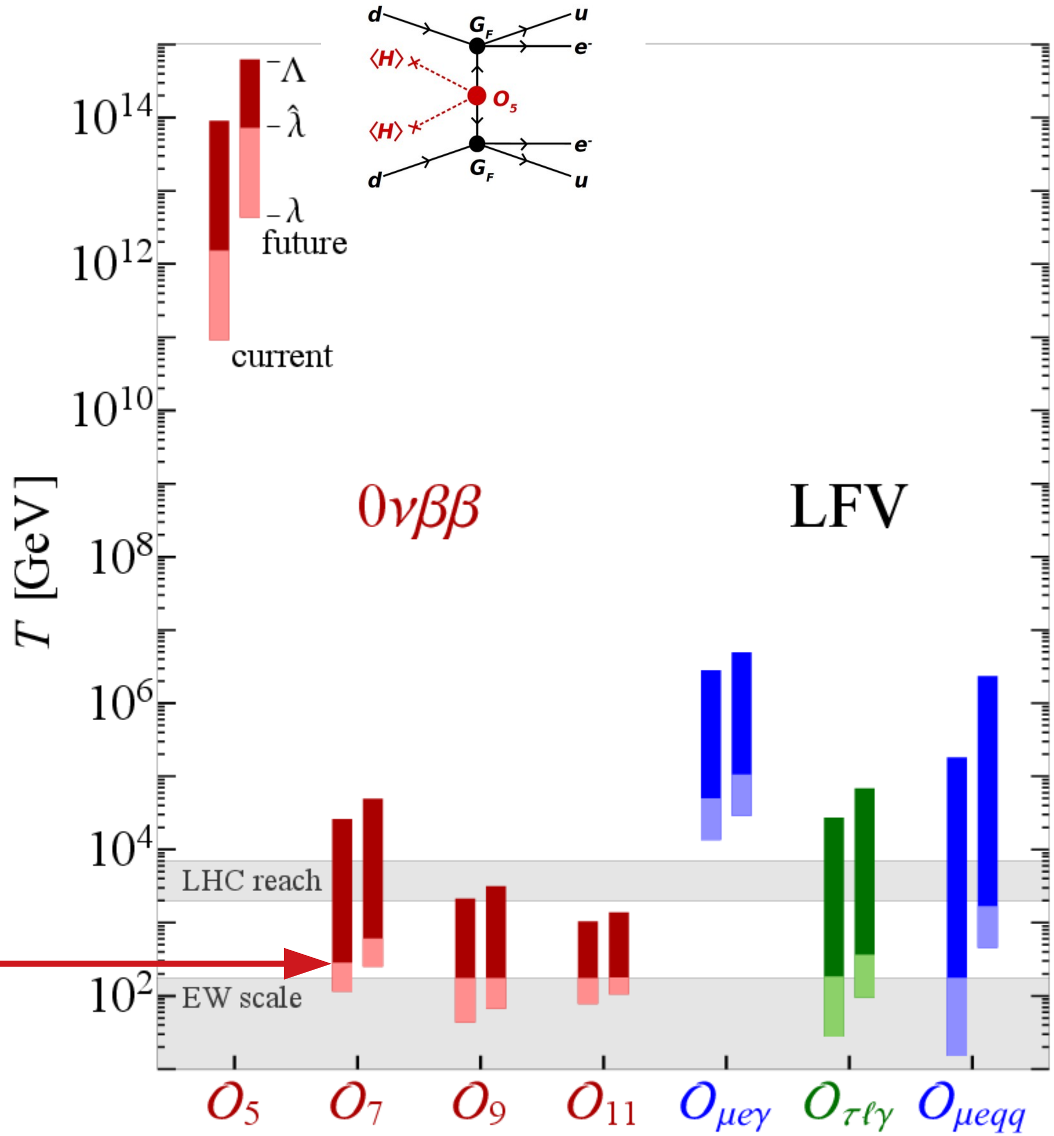
- washout efficient if

$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H} \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}} = c'_D \frac{\Lambda_{\text{Pl}}}{\Lambda_D} \left(\frac{T}{\Lambda_D}\right)^{2D-9} > 1$$

If 0νßß is observed, washout efficient in the temperature interval

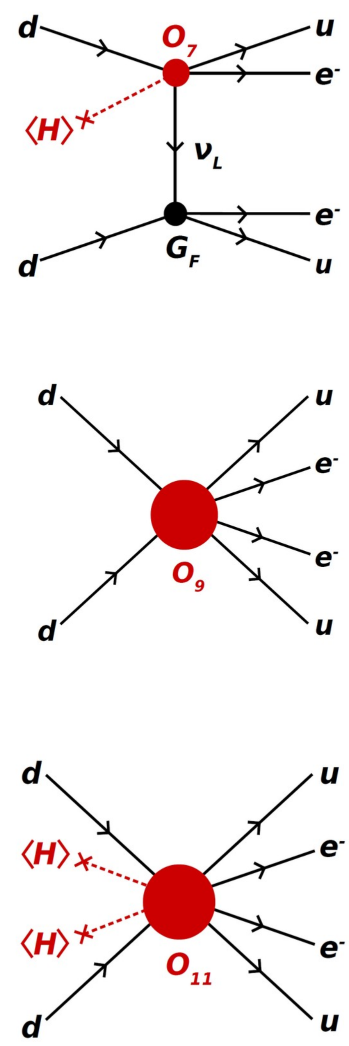
$$\Lambda_D \left(\frac{\Lambda_D}{c'_D \Lambda_{\text{Pl}}}\right)^{\frac{1}{2D-9}} \equiv \lambda_D < T < \Lambda_D$$

0νββ and Baryogenesis



limit above which the washout is highly effective

$$\frac{\Gamma_W}{H} > 1$$

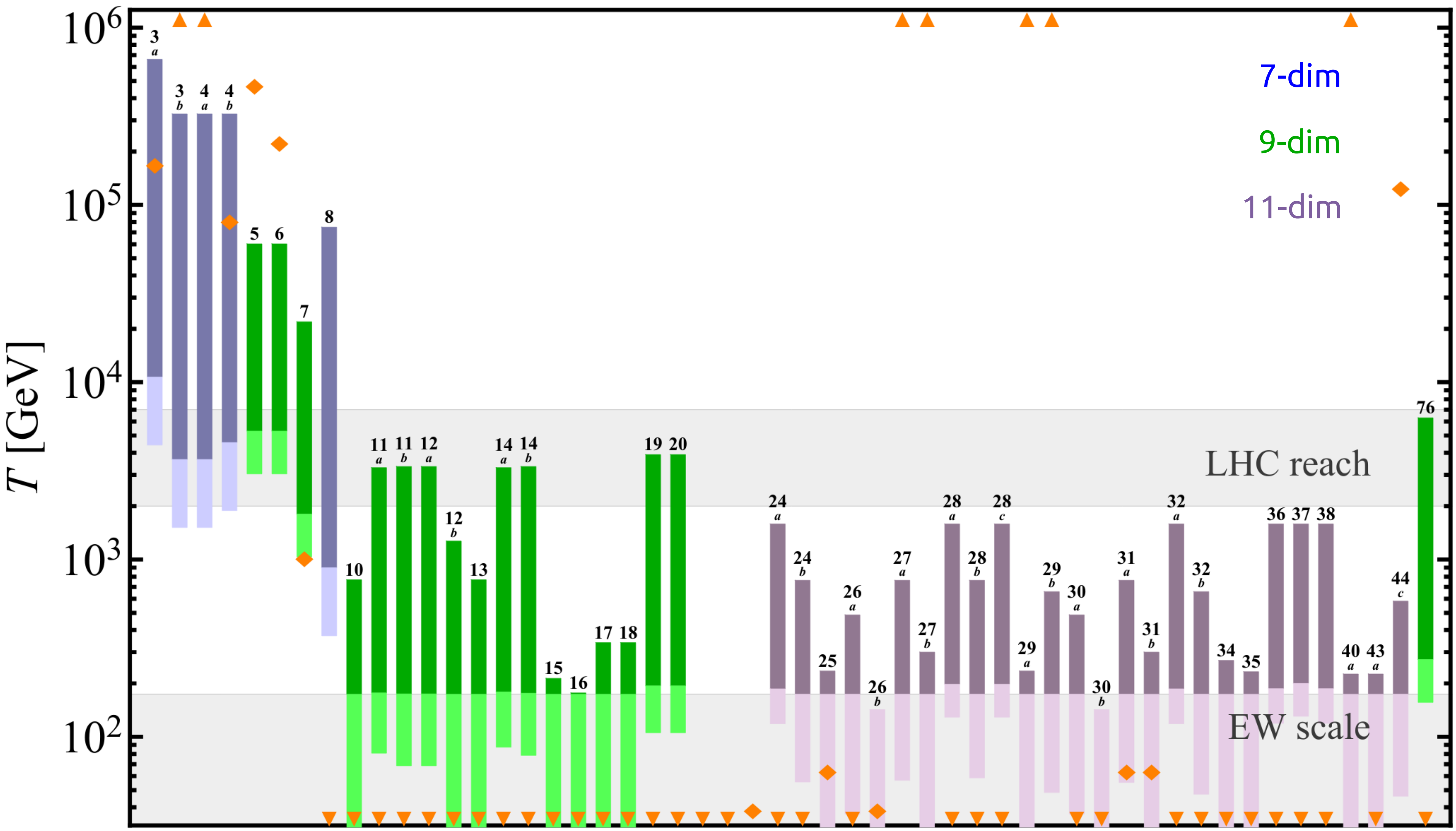


Potential to falsify baryogenesis models!

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Lepton asymmetry washout

1st generation couplings

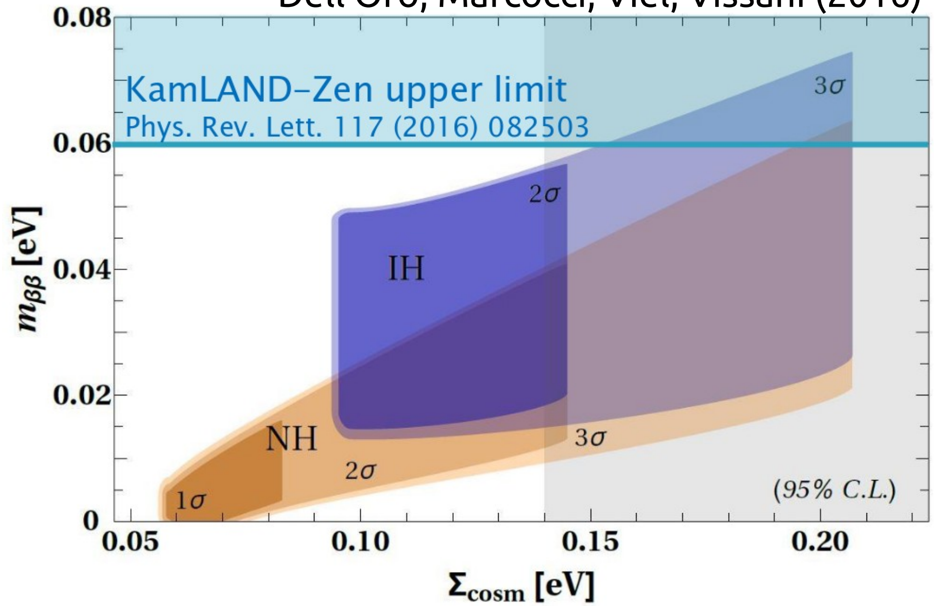


Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

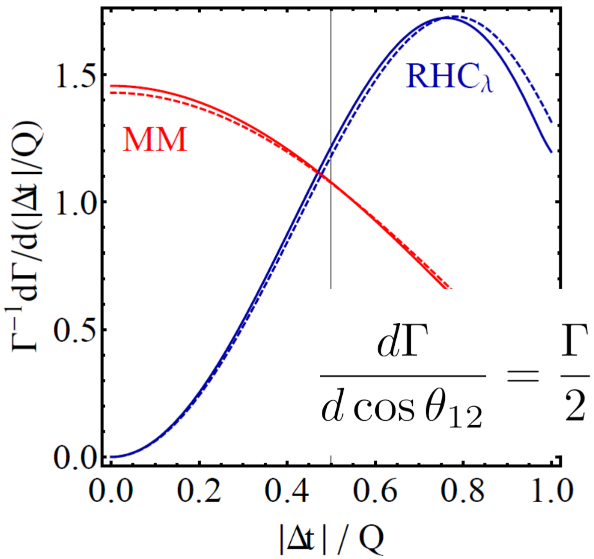
Distinguishing different operators

- **discrepancy** between sum of neutrino masses from **cosmology** and **0νββ half life** measurements could indicate non-standard mechanism

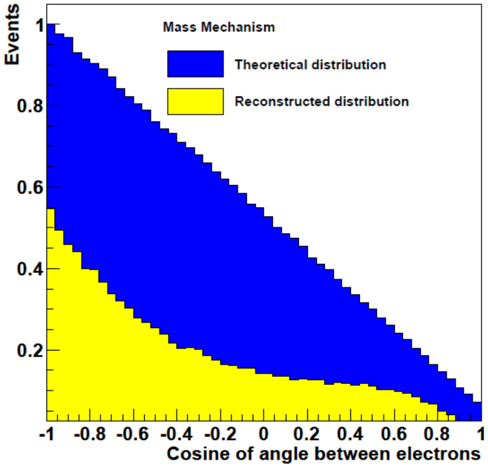
Dell'Oro, Marcocci, Viel, Vissani (2016)

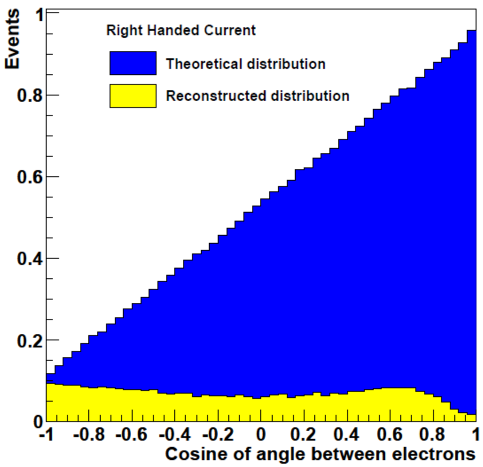


- **Angular distributions** allows to discriminate O_7 from others, due to e^-_R and e^+_L in the final state



$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$





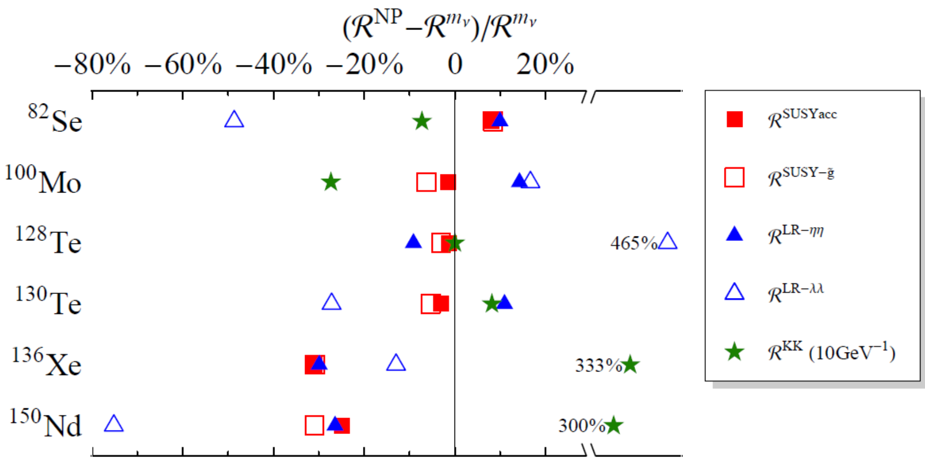
Ali, Borisov, Zhuridov (2006), SuperNemo, Arnold et al. (2010)

Distinguishing different operators

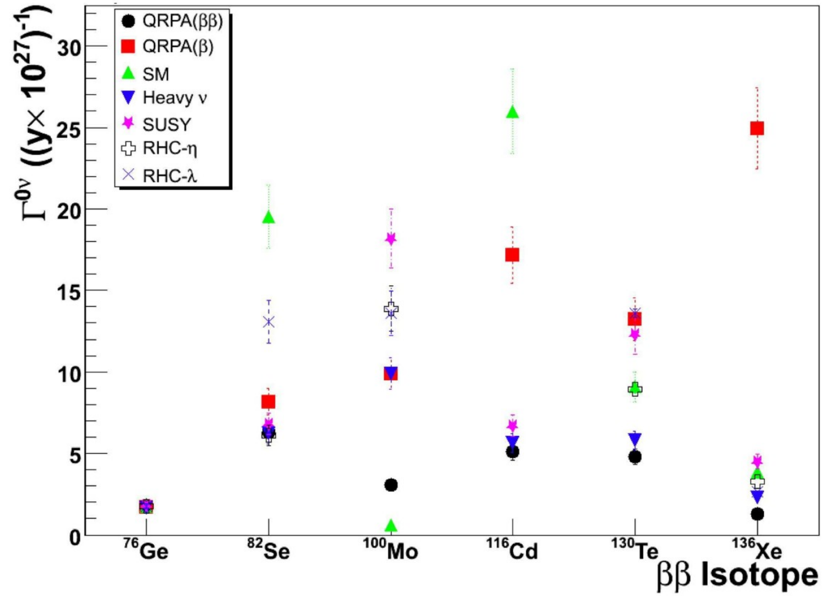
- distinguishing between different mechanisms via **measurements in different isotopes**

$$[T_{1/2}^{NP}]^{-1} = \epsilon_{NP}^2 G^{NP} |\mathcal{M}^{NP}|^2$$

$$\frac{T_{1/2}(^AX)}{T_{1/2}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}(^{76}\mathrm{Ge})|^2 G(^{76}\mathrm{Ge})}{|\mathcal{M}(^AX)|^2 G(^AX)}$$



Deppisch, Päs (2006)



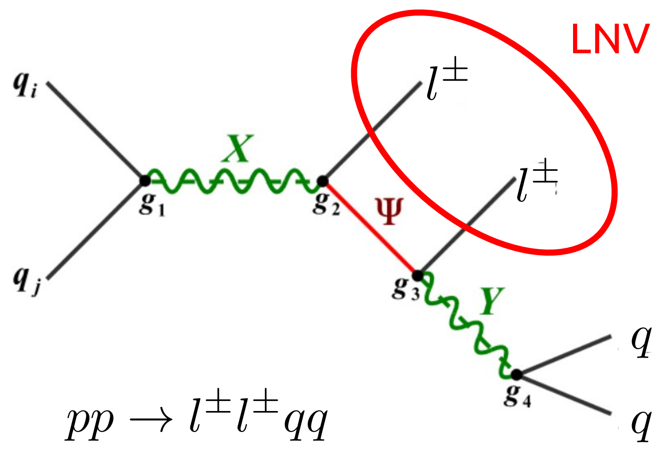
Isotope Ordering	Confidence Level	Number of Isotopes 2	3	4	5	6
Atomic Number	90%	<2%	8%	16%	23%	24%
	68%	<2%	19%	36%	45%	48%
$\Gamma^{0\nu}$ Spread	90%	6%	18%	27%	27%	24%
	68%	13%	29%	41%	42%	47%
Experimental Readiness	90%	3%	11%	24%	24%	24%
	68%	7%	18%	46%	47%	47%
Alternative Ordering	90%	3%	11%	17%	15%	24%
	68%	7%	18%	34%	32%	47%
Experimental Readiness (All 7 models, no ^{116}Cd)	90%	< 2%	6%	14%	16%	
	68%	< 2%	12%	22%	24%	

Gehmann, Elliot (2007)

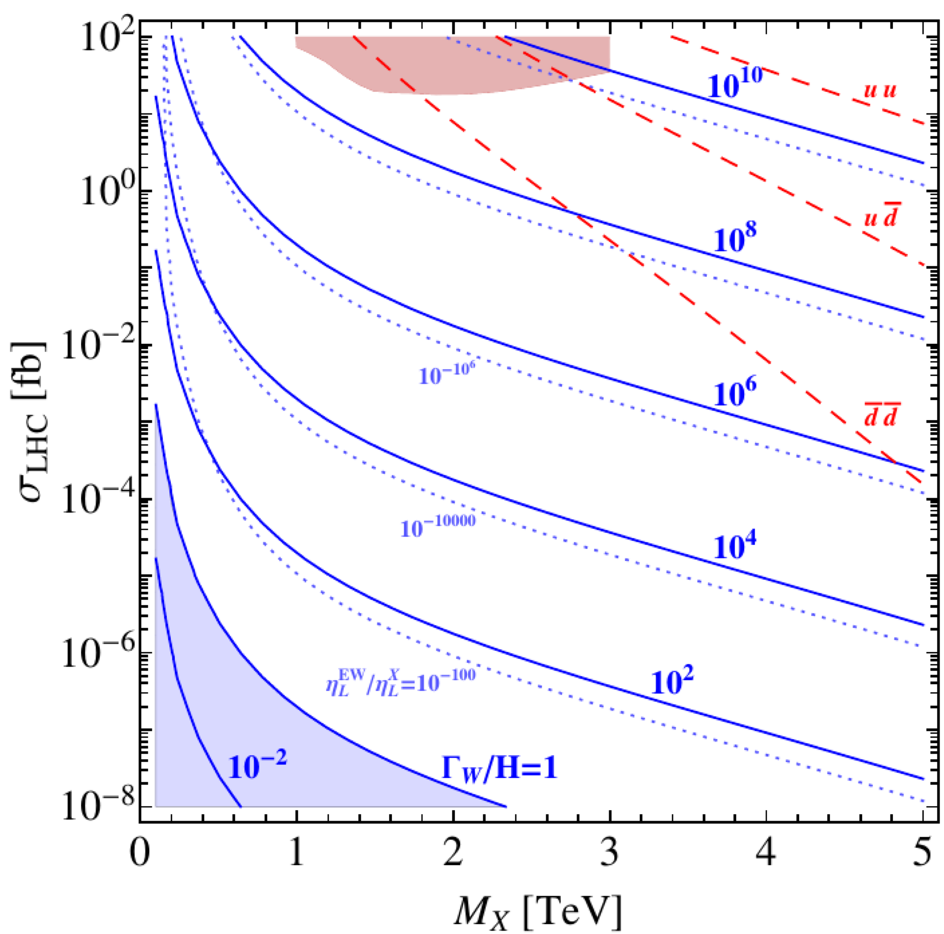
- observation of 0νββ via O_9 and O_{11} will **imply observation of LNV at LHC**

Probing LNV interactions – LHC

Washout processes could be observable at the LHC



$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\mathrm{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}$$



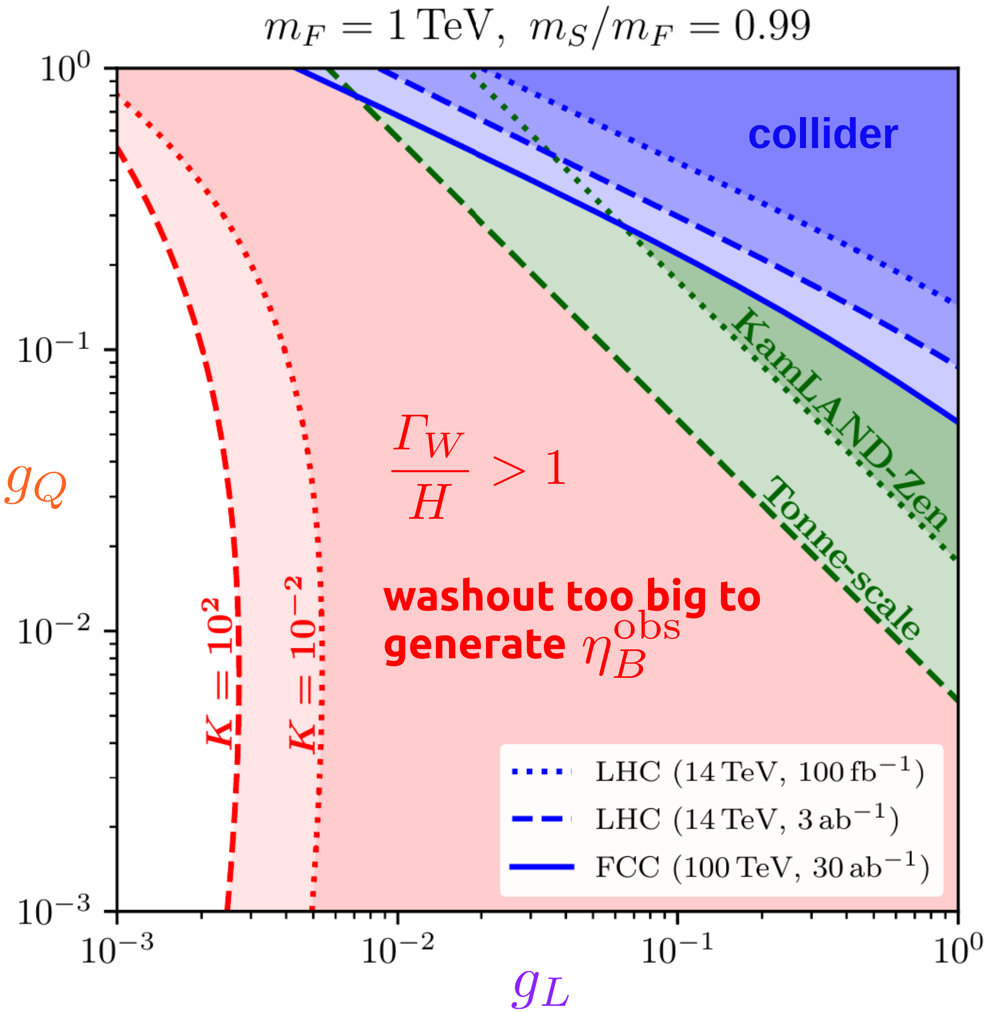
Observation of any washout process at LHC would falsify high scale baryogenesis!

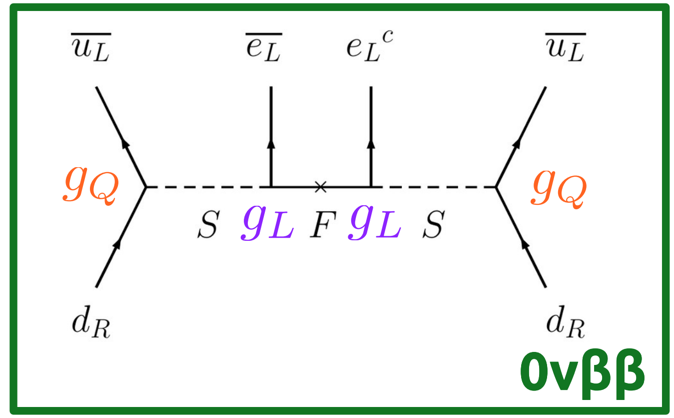
(scale of asymmetry generation *above* M_X)

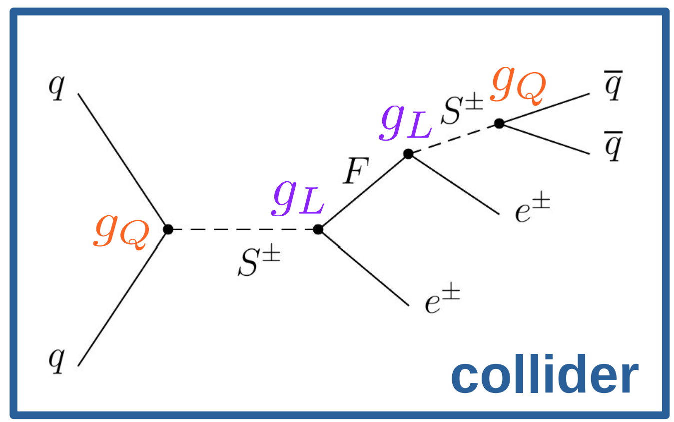
Deppisch, JH, Hirsch, Phys. Rev. Lett. (2014)
Deppisch, JH, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

Combining LHC & 0νββ

$$\mathcal{L} = g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2}\overline{F^c}F + g_S(S^\dagger S)^2 + \lambda_{HS}(S^\dagger H)^2 + \text{h.c.}$$



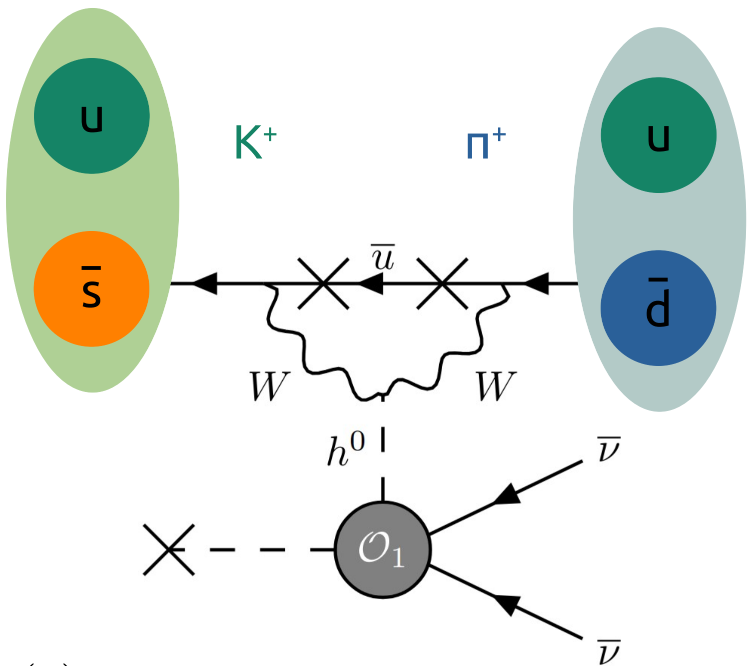




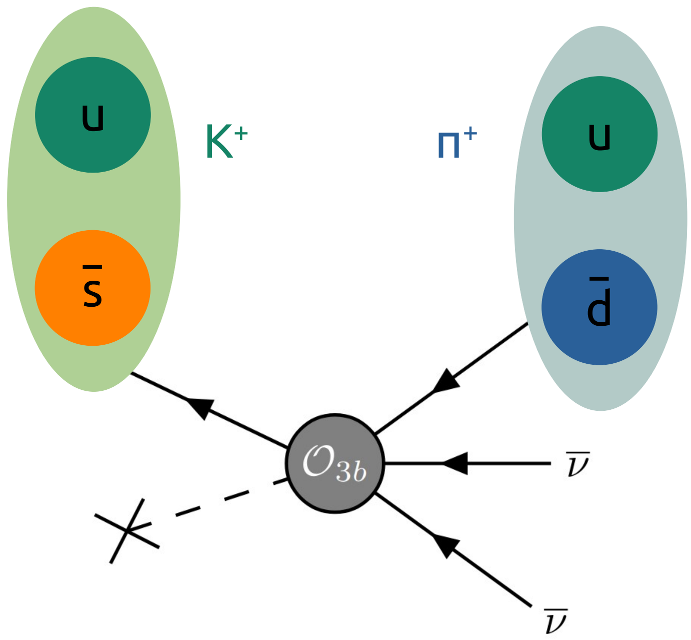
Comprehensive analysis confirms EFT results and shows interesting interplay between collider and 0νββ reach.

JH, Ramsey-Musolf, Shen, Urrutia, in preparation

Constraining LNV interactions with rare kaon decays



$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$



$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

- GIM suppressed

Not explicit LNV!

- No GIM suppression
- Includes first and second generation

How are higher dimensional operators constraint by rare kaon decays?

Deppisch, Fridell, JH (2020)

Constraining power at E949

- **SM**, lepton number **conserving vector** current

$$\mathcal{L}_{\mathrm{SM}}^{K\to\pi\nu\bar{\nu}} = \frac{1}{\Lambda_{\mathrm{SM}}^2}\left(\bar{\nu}_i\gamma^\mu\nu_i\right)\left(\bar{d}\gamma_\mu s\right)$$

- **BSM**, lepton number **violating scalar** current

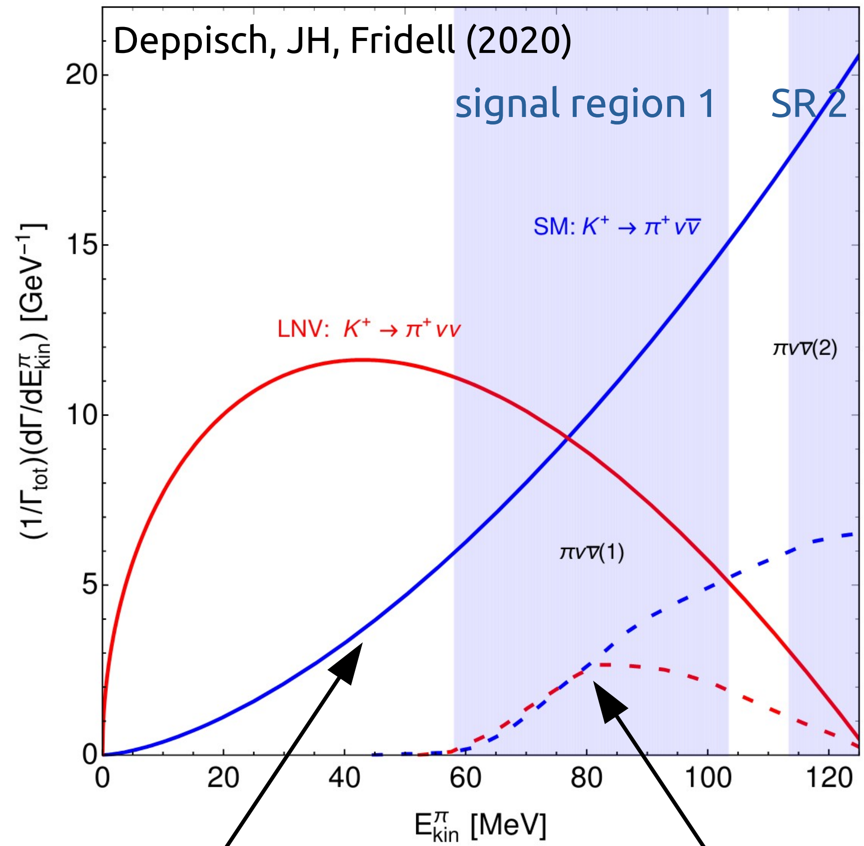
$$\mathcal{L}_{\mathrm{BSM}}^{K\to\pi\nu\nu} = \frac{v}{\Lambda_{\mathrm{BSM}}^2}\left(\nu_i\nu_j\right)\left(\bar{d}s\right)$$

→ **different phase space distribution**

- **different acceptance:**

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})_{\mathrm{E949}}^{\mathrm{vector}} < 3.35\times10^{-10} \quad \text{at } 90\%\ \mathrm{CL}$$

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})_{\mathrm{E949}}^{\mathrm{scalar}} < 21\times10^{-10} \quad \text{at } 90\%\ \mathrm{CL}$$

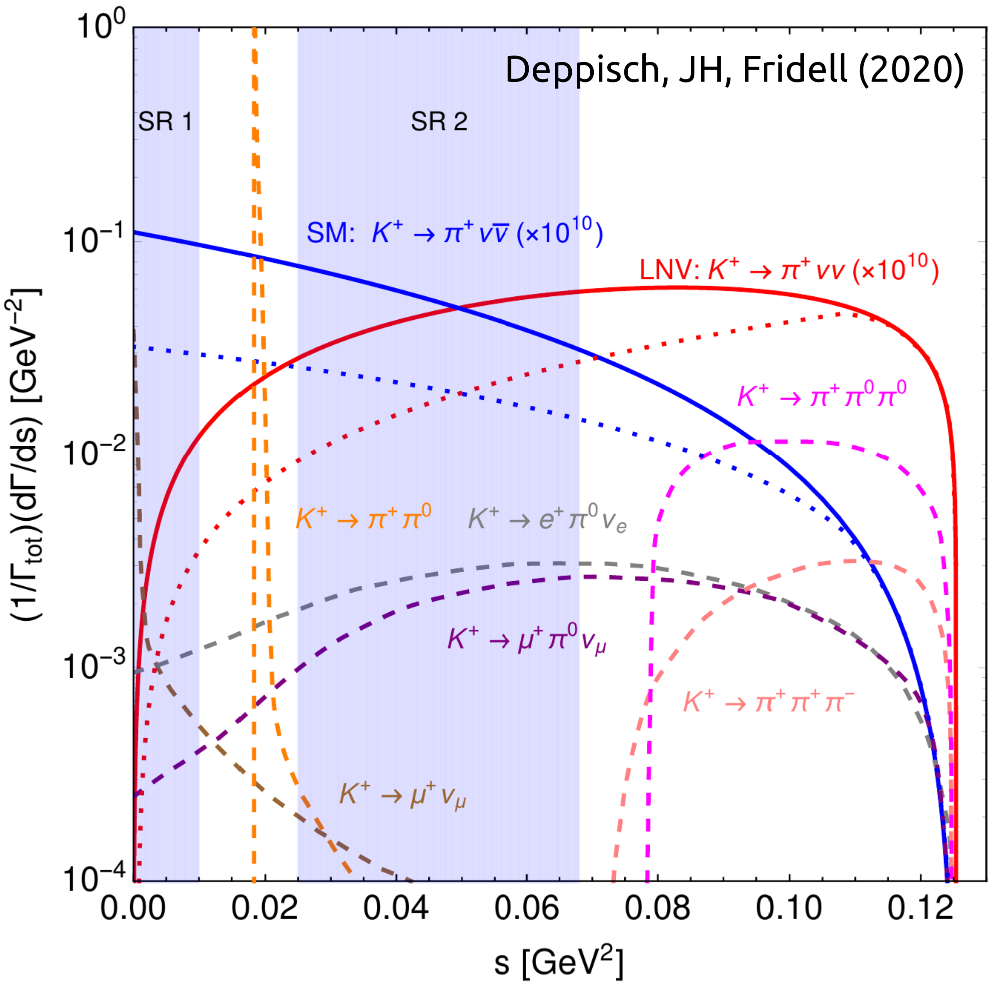


theoretical distribution

after experimental acceptance

Deppisch, Fridell, JH (2020)

Constraining power at NA62



$$s = (E_K - E_\pi)^2$$

Summary of sensitivity to scalar current (based on kinematics only):

Experiment	SM (vector)	LNV (scalar)
NA62 SR 1	6%	0.3%
NA62 SR 2	17%	15%
E949 $\pi\nu\bar{\nu}(1)$	29%	2%
E949 $\pi\nu\bar{\nu}(2)$	45%	38%
KOTO	64%	30%

Experiments are generally more sensitive to vector currents

Possibility to disentangle a possible signal by improving on experimental sensitivity and strategy?

Deppisch, Fridell, JH (2020)

Summary

Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\text{NP}}_{ijkn}$ [TeV]	$\hat{\lambda}$ [TeV]
$K^+ \to \pi^+ \nu\nu$	$\text{BR}^{\text{NA62}}_{\text{future}} < 1.11 \times 10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 19.6$	0.213
$K^+ \to \pi^+ \nu\nu$	$\text{BR}^{\text{NA62}}_{\text{current}} < 1.78 \times 10^{-10}$ [67]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 17.2$	0.196
$K_L \to \pi^0 \nu\nu$	$\text{BR}^{\text{KOTO}}_{\text{current}} < 3.0 \times 10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$	0.178
$B^+ \to \pi^+ \nu\nu$	$\text{BR} < 1.4 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibd} > 1.4$	0.174
$B^+ \to K^+ \nu\nu$	$\text{BR} < 1.6 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibs} > 1.4$	0.174
$B^0 \to \pi^0 \nu\nu$	$\text{BR} < 9 \times 10^{-6}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibd} > 1.5$	0.174
$B^0 \to K^0 \nu\nu$	$\text{BR} < 2.6 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibs} > 1.3$	0.174
$K^+ \to \mu^+ \bar{\nu}_e$	$\text{BR} < 3.3 \times 10^{-3}$ [32]	$\mathcal{O}_{3a}$	$\Lambda_{\mu esu} > 2.4$	0.174
$\pi^+ \to \mu^+ \bar{\nu}_e$	$\text{BR} < 1.5 \times 10^{-3}$ [32]	$\mathcal{O}_{3a}$	$\Lambda_{\mu eud} > 1.9$	0.174
$\pi^0 \to \nu\nu$	$\text{BR} < 2.9 \times 10^{-13}$ [78]	$\mathcal{O}_{3b}$	$\Lambda_{\nu\nu ud} > 3.4$	0.174
$0\nu\beta\beta$	$T^{^{136}\text{Xe}}_{1/2} \geq 1.07 \times 10^{26}$ yrs [79]	$\mathcal{O}_{3b}$	$\Lambda_{eeud} > 330$	3.5
$\mu^- \to e^+$	$R^{\text{Ti}}_{\mu^- e^+} < 1.7 \times 10^{-12}$ [80]	$\mathcal{O}_{14b}$	$\Lambda_{\mu eud} > 0.01$	0.174

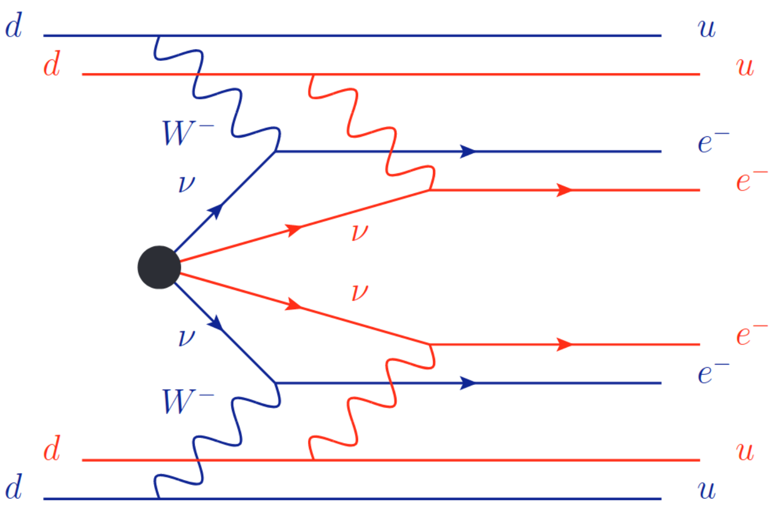
Bright future perspective – B-meson constraints still in LHC reach. Could imply strong lepton asymmetry washout*).

***) If LNV interaction is confirmed.**

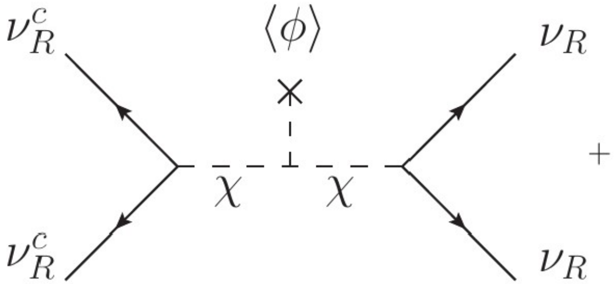
Is LNV only possible with Majorana particles?

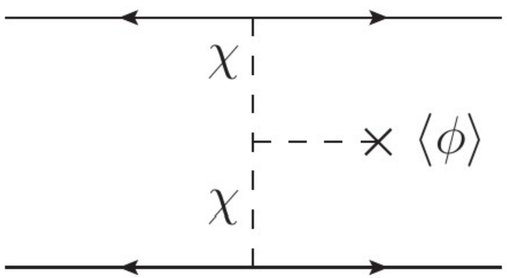
Neutrinoless Quadruple Decay

$$(A, Z) \to (A, Z+4) + 4e^-$$



$$\Delta(B-L) = 4$$





$$\boxed{\frac{\tau_{1/2}^{0\nu4\beta}}{\tau_{1/2}^{2\nu2\beta}} \simeq \left(\frac{Q_{0\nu2\beta}}{Q_{0\nu4\beta}}\right)^{11}\left(\frac{\Lambda^4}{q^{12}G_F^4}\right) \simeq 10^{46}\left(\frac{\Lambda}{\text{TeV}}\right)^4}$$

pessimistic estimate – light mediators, resonances…

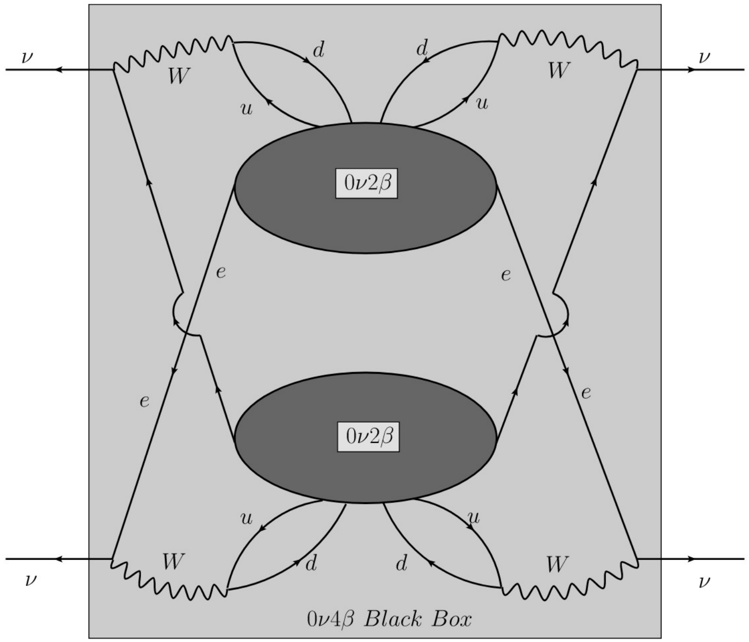
NO!

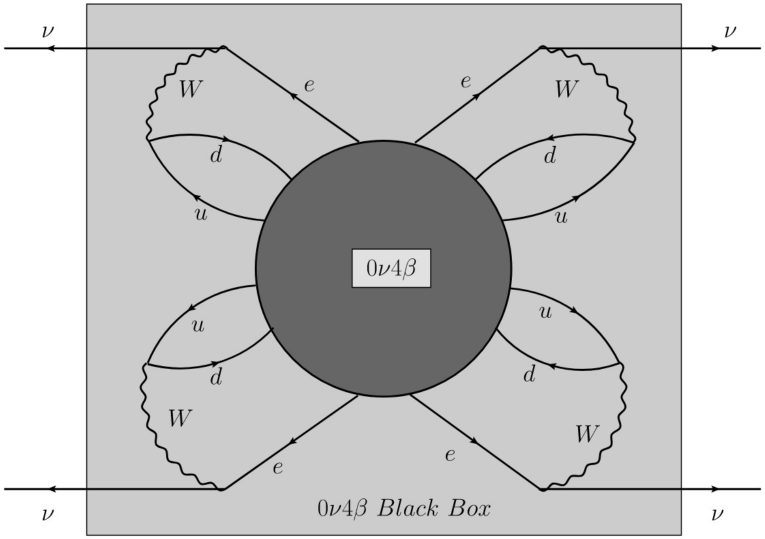
Majorana Neutrinos are **not** generally a pre-requisite for LNV

LNV with **Dirac neutrinos** @ Neutrinoless Quadruple Decay! **(ΔL = 4)**

Heeck, Rodejohann (2013)

Can one ever prove neutrinos are Dirac?





$$R = \frac{\Gamma_{0\nu 2\beta}}{\Gamma_{0\nu 4\beta}}$$

$$R = \frac{Q_{\beta\beta}^{5}(\frac{1}{\Lambda^5})^2 q^6}{Q_{4\beta}^{11}(\frac{1}{\Lambda^{14}})^2 q^{18}} \sim 10^{82}$$

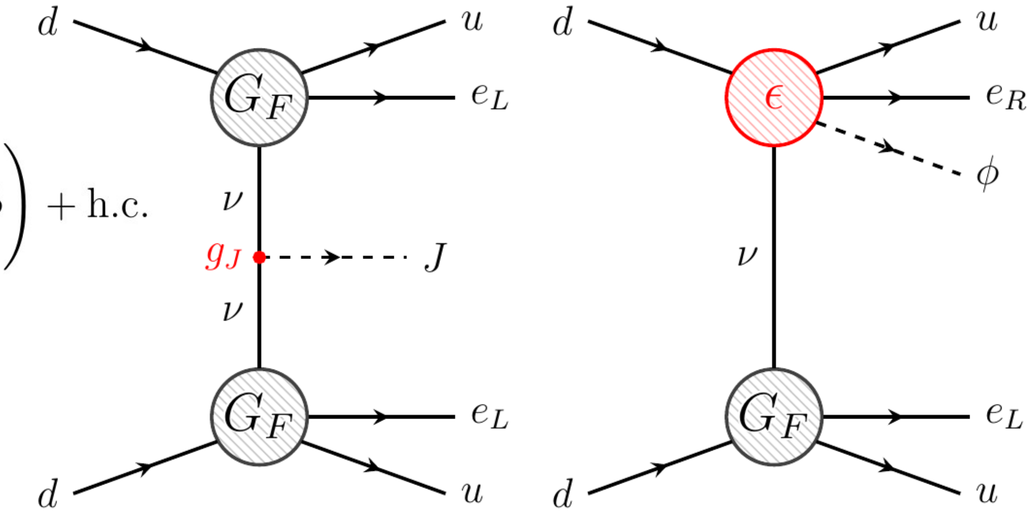
Should a **0v4β decay** signal ever be established, **unaccompanied by 0v2β** decays, then one would **rule out Majorana neutrinos**

Caveats may exist?

Hirsch, Srivastava, Valle (2018)

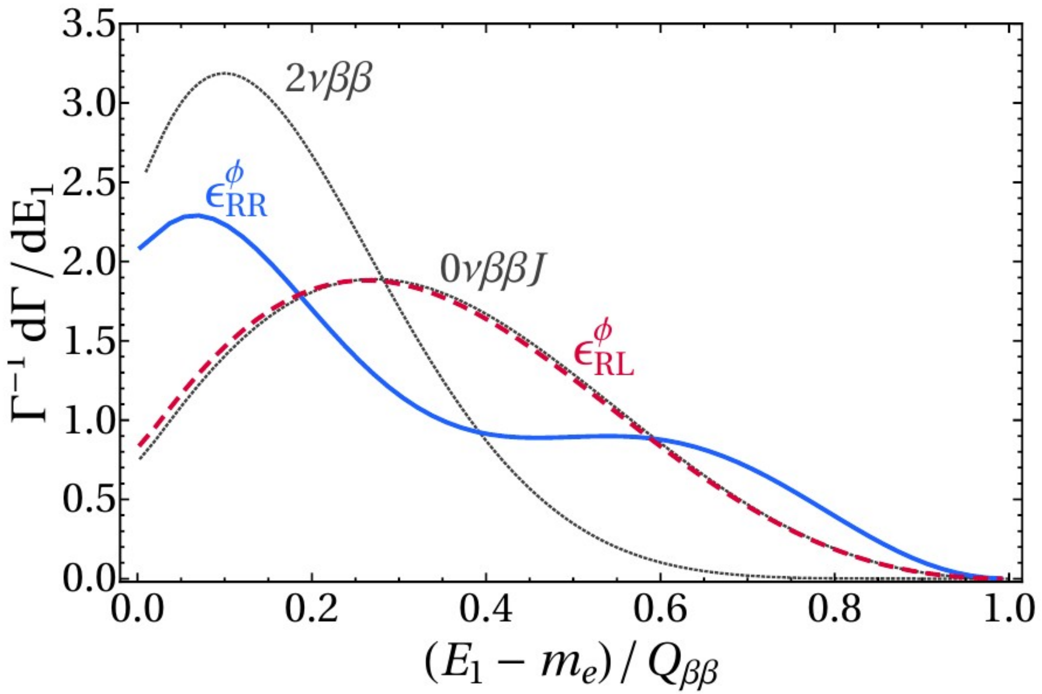
Non-standard Majoron Emission

$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu}\phi \right) + \text{h.c.}$$



Isotope	$T_{1/2}$ [y]	$\lvert\epsilon_{RL}^\phi\rvert$	$\lvert\epsilon_{RR}^\phi\rvert$
^{82}Se	3.7×10^{22} [14]	4.1×10^{-4}	4.6×10^{-2}
^{136}Xe	2.6×10^{24} [13]	1.1×10^{-4}	1.1×10^{-2}
^{82}Se	1.0×10^{24}	8.0×10^{-5}	8.8×10^{-3}
^{136}Xe	1.0×10^{25}	5.7×10^{-5}	5.8×10^{-3}

$$\Lambda_{\text{NP,RL}}^{\text{fut}} \approx 1.3\text{TeV}$$
$$\Lambda_{\text{NP,RR}}^{\text{fut}} \approx 270\text{GeV}$$



New type of interaction distinguishable from background

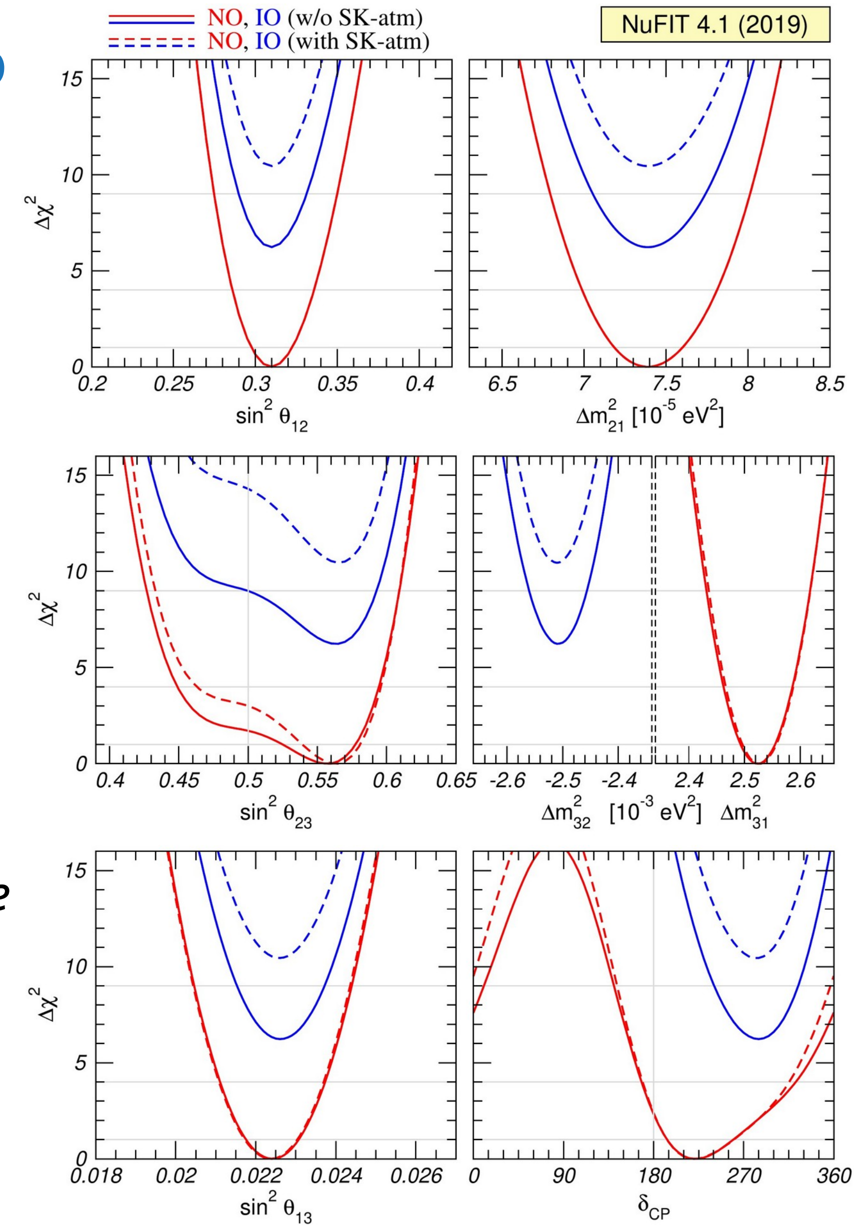
Cepedello, Deppisch, Gonzalez, Hati, Hirsch, Päs (2019)

Neutrino Oscillations & 0νββ

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} \, |\nu_\alpha\rangle$$

$\vert\nu_\alpha\rangle$	flavour eigenstates
$\vert\nu_i\rangle$	mass eigenstates
$U_{\alpha i}$	Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

- **Solar experiments**
  Homestake, Chlorine, Gallex/GNO, SAGE, (Super) Kamiokande, SNO, Borexino
- **Atmospheric experiments**
  IceCube, ANTARES, DeepCore, Super-Kamiokande
- **Reactor experiments**
  KamLAND, Double Chooz, Daya Bay
- **Accelerator experiments**
  T2K, MINOS, NOvA

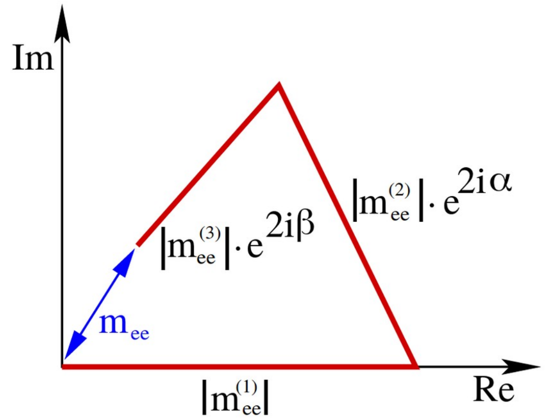


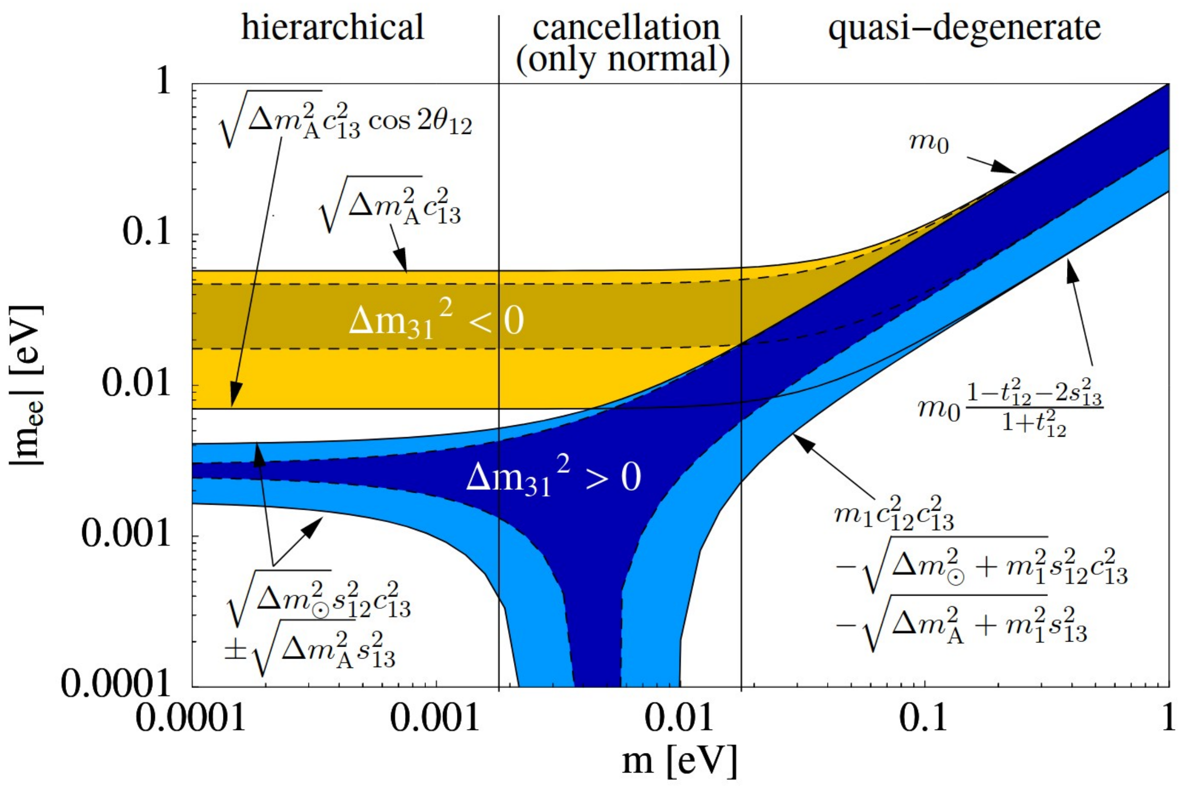
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Oscillations & 0νββ

$$\langle m_{ee} \rangle = \left| c_{12}^2 c_{13}^2 \, m_1 + s_{12}^2 c_{13}^2 \, m_2 \, e^{2i\phi_{12}} + s_{13}^2 \, m_3 \, e^{2i\phi_{13}} \right|$$

- Uncertainty from **unknown Majorana phase**
- **Quasi-degenerate** region above 0.2 eV
- Accidental **cancellation** for NO

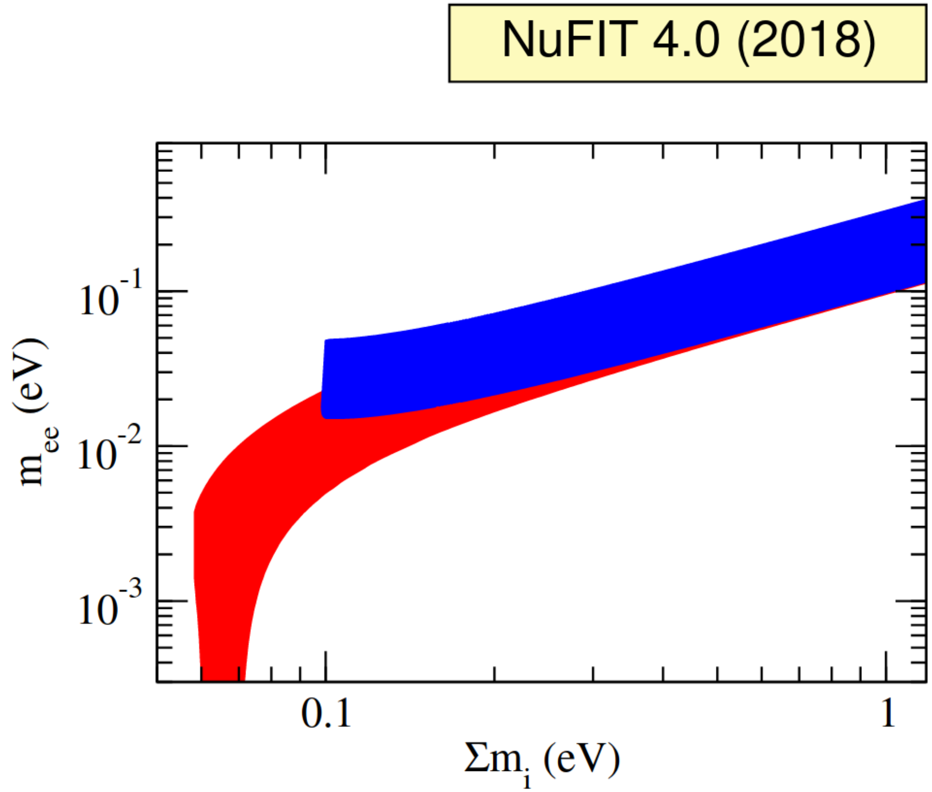




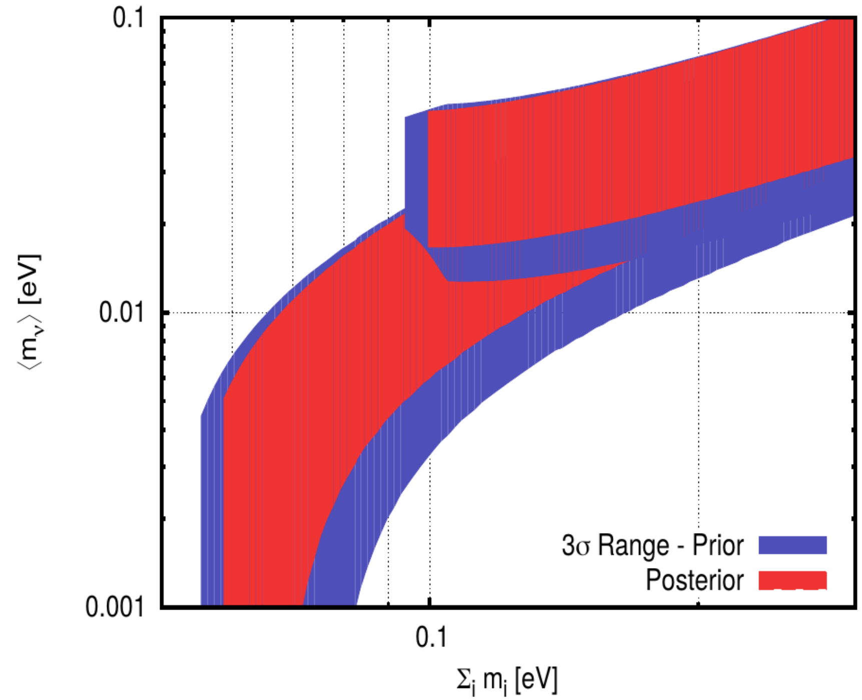
Lindner, Merle, Rodejohann (2006)

Neutrino Oscillations & 0νββ

Combined fit



Future projection with JUNO



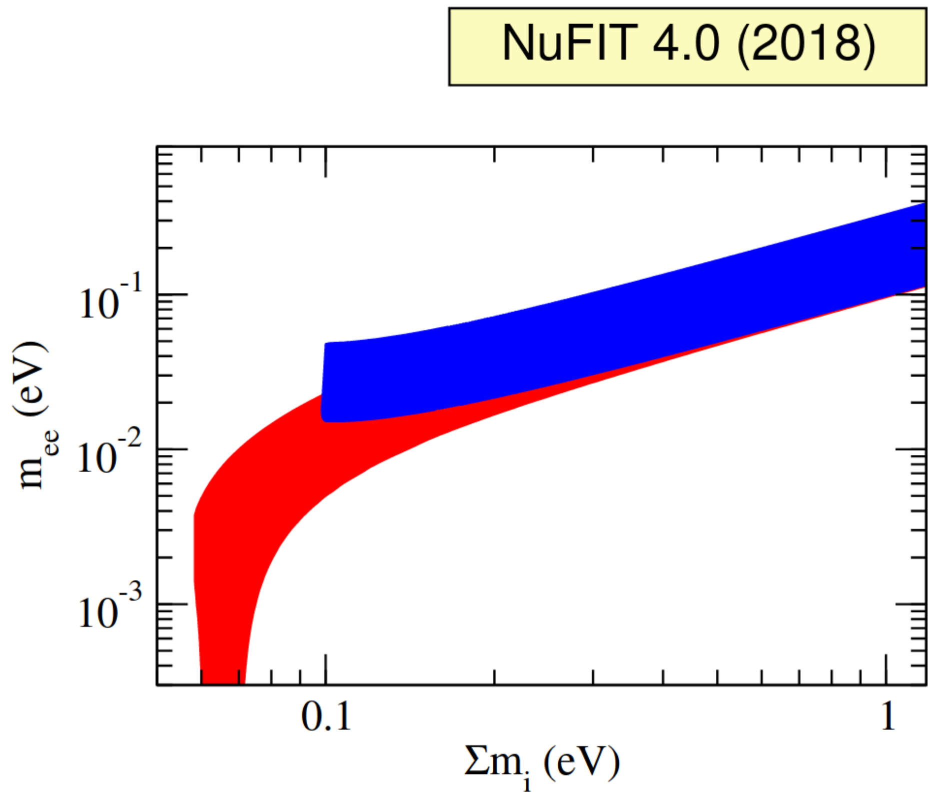
$$\langle m_\nu \rangle_{\min}^{\mathrm{IO}} \rightarrow \sqrt{\Delta m_a^2}(c_s^2 - s_s^2)c_r^2$$

JUNO can determine **minimal value** of the effective mass with **almost no uncertainty** → fixes the half life that needs to be addressed

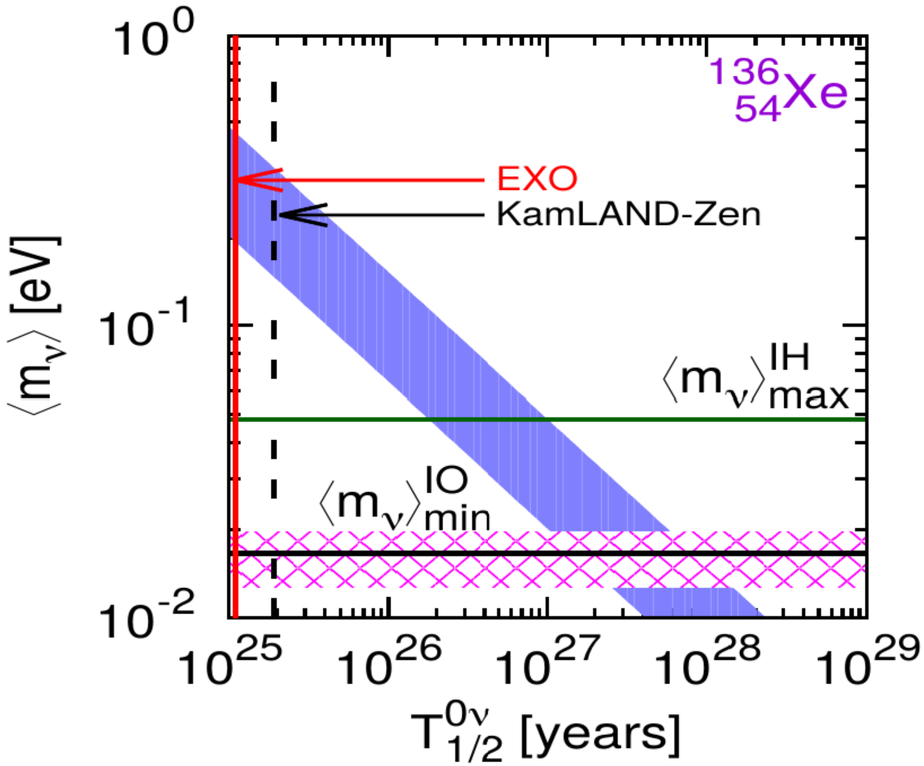
Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz (2018+)
Anamiati, Romeri, Hirsch, Ternes, Tortola (2019+)
Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo (2017+)
Ge, Rodejohann (2018)

Neutrino Oscillations & 0νββ

Combined fit



Future projection with JUNO



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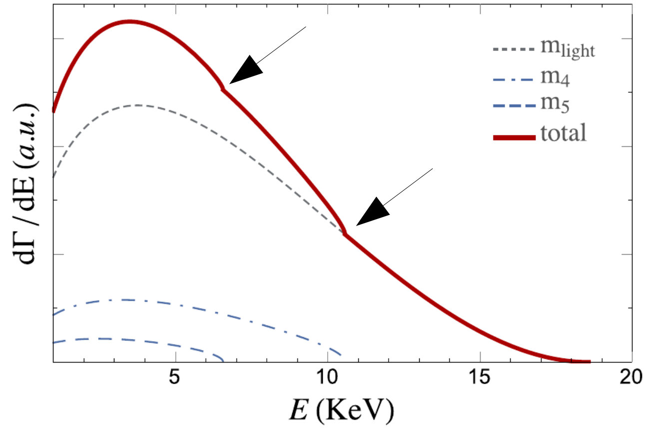
Ge, Rodejohann (2015+)

Light Sterile Neutrinos – Interplay 0νββ & KATRIN

Hypothesis: KATRIN sees a kink



$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

$$m_4 \in [1\ \mathrm{KeV}, 18.5\ \mathrm{KeV}]\,, \quad |U_{e4}|^2 > 10^{-6}\,.$$

$$\frac{d\Gamma}{dE} = \Theta\left(E_0 - E - m_\beta\right)\left(1 - |U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta) + \Theta\left(E_0 - E - m_4\right)|U_{e4}|^2\frac{d\Gamma}{dE}(m_4)$$

Assumption: 3 active + 1 sterile neutrino:

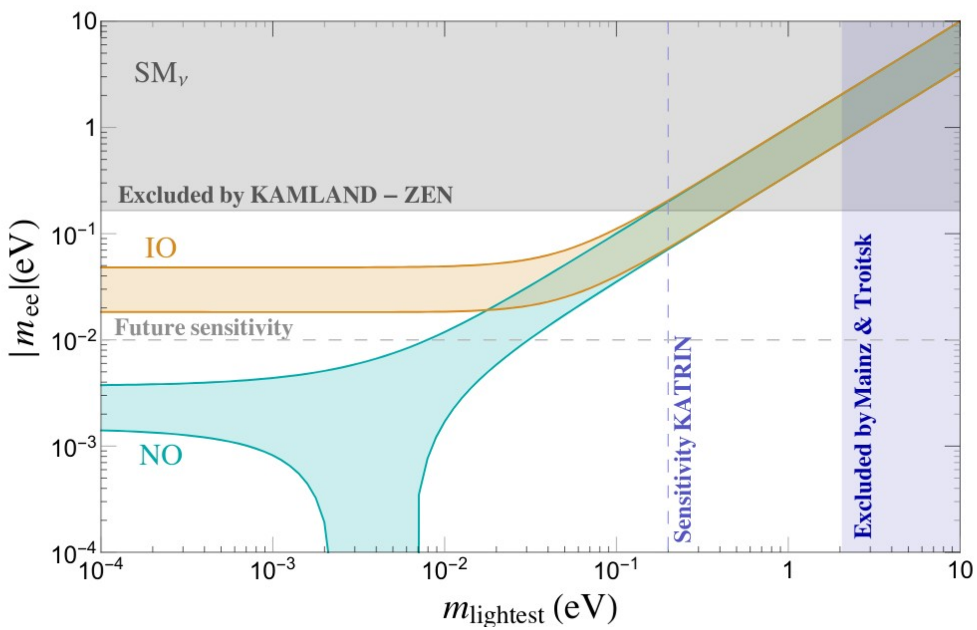
$$-\mathcal{L}_{\mathrm{cc}} = \frac{g}{\sqrt{2}}U_{ji}\bar{\ell}_j\gamma^\mu P_L \nu_i W_\mu^- + \mathrm{H.c.}$$

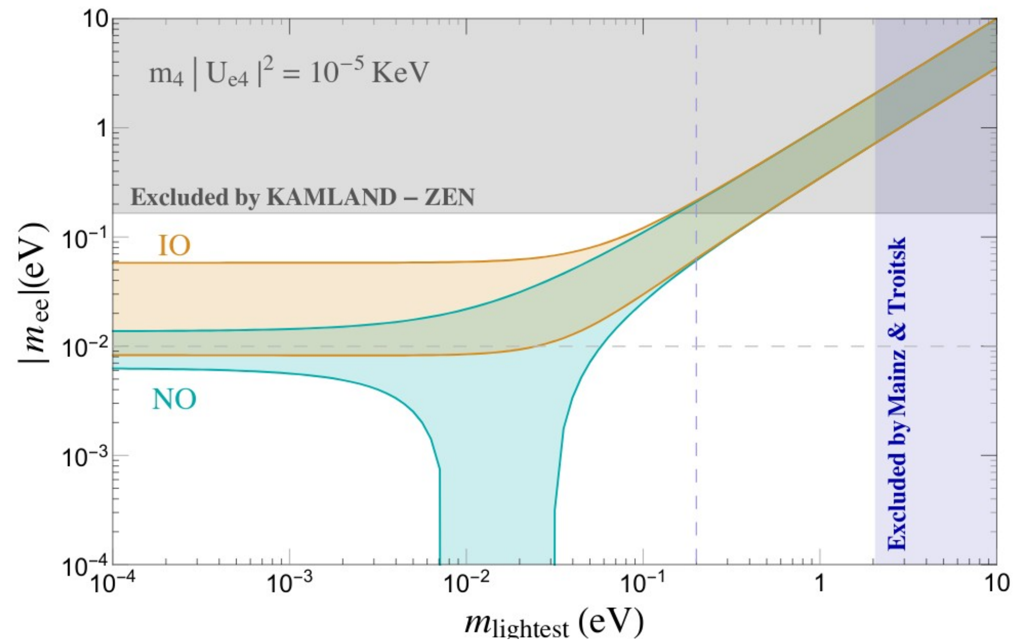
Impact on neutrinoless double beta decay:

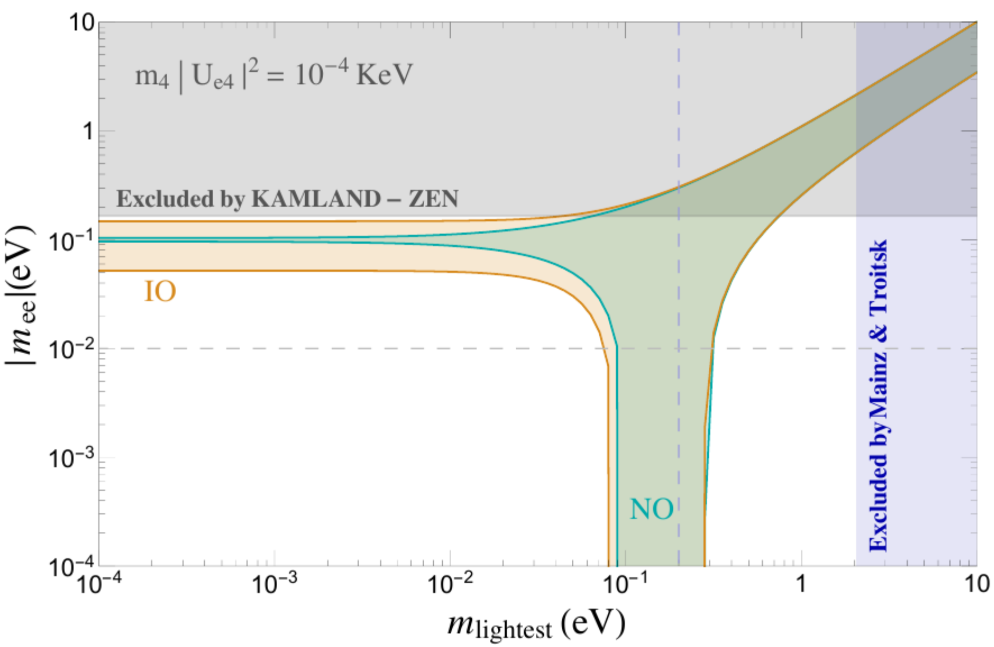
$$m_{ee}^{(3+1)} = \sum_{i=1}^{4} U_{ei}^2\, p^2 \frac{m_i}{p^2 - m_i^2} \simeq \sum_{i=1}^{4} U_{ei}^2\, m_i \equiv m_{ee}^{(\mathrm{SM}_\nu)} + m_4 U_{e4}^2$$

Abada, Hernandez-Cabezudo, Marcano (2019)

Light Sterile Neutrinos – Interplay 0νββ & KATRIN







- possible kink @ KATRIN would imply that IO and NO might **not be distinguishable** anymore with 0νββ
- **Observation** of 0νββ would not necessarily imply IO
- **Non-observation** would not rule out IO due to cancellations for large enough $m_4 U^2_{e4}$

Abada, Hernandez-Cabezudo, Marcano (2019)

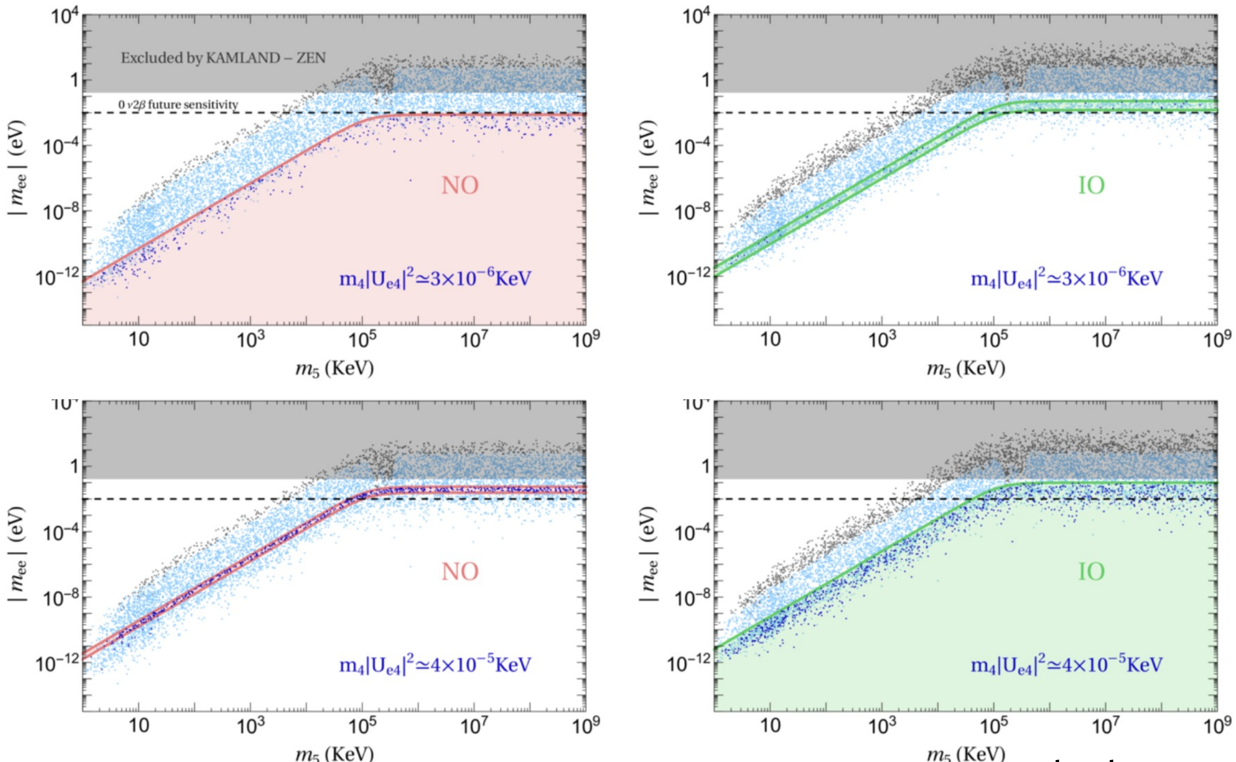
Light Sterile Neutrinos – Interplay 0νββ & KATRIN

Assumption: 3 active + 2 sterile neutrinos (See saw type-I):

$$m_{ee} = \sum_{i=1}^{5} U_{ei}^2\, p^2 \frac{m_i}{p^2 - m_i^2} \simeq m_{ee}^{(3+1)} + U_{e5}^2\, m_5 \frac{p^2}{p^2 - m_5^2}$$

1st sterile neutrino in KATRIN reach, 2nd variable

$$m_{ee} \simeq m_{ee}^{(3+1)} \times \left[1 - \frac{p^2}{p^2 - m_5^2}\right]$$



Abada, Hernandez-Cabezudo, Marcano (2019)

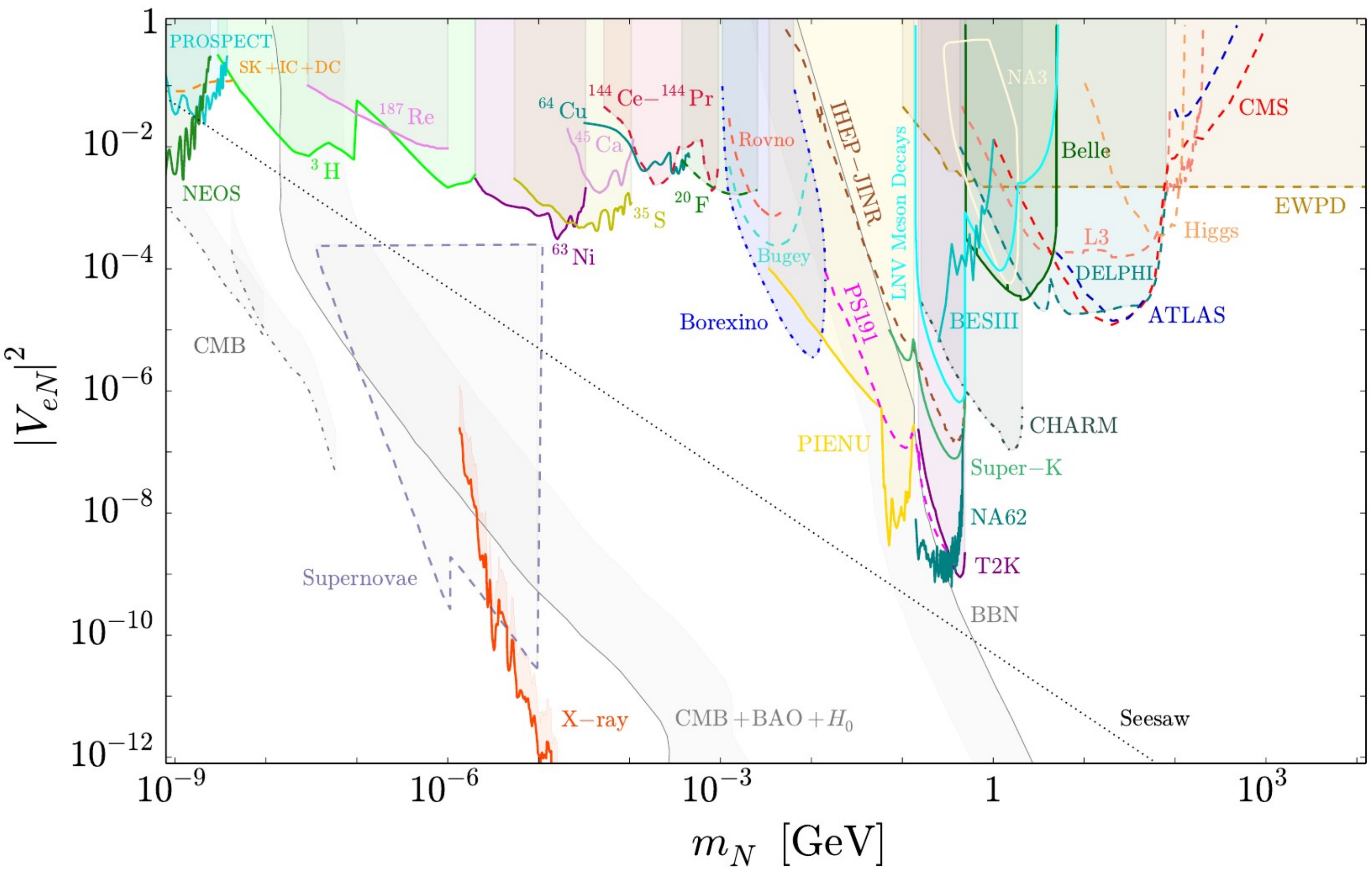
Interesting interplay between KATRIN & 0vbb prospects

Isotope dependent cancellation between two **different** exchange mechanisms (two different NMEs)

Pascoli, Mitra, Wong (2014)

Heavy Sterile Neutrinos

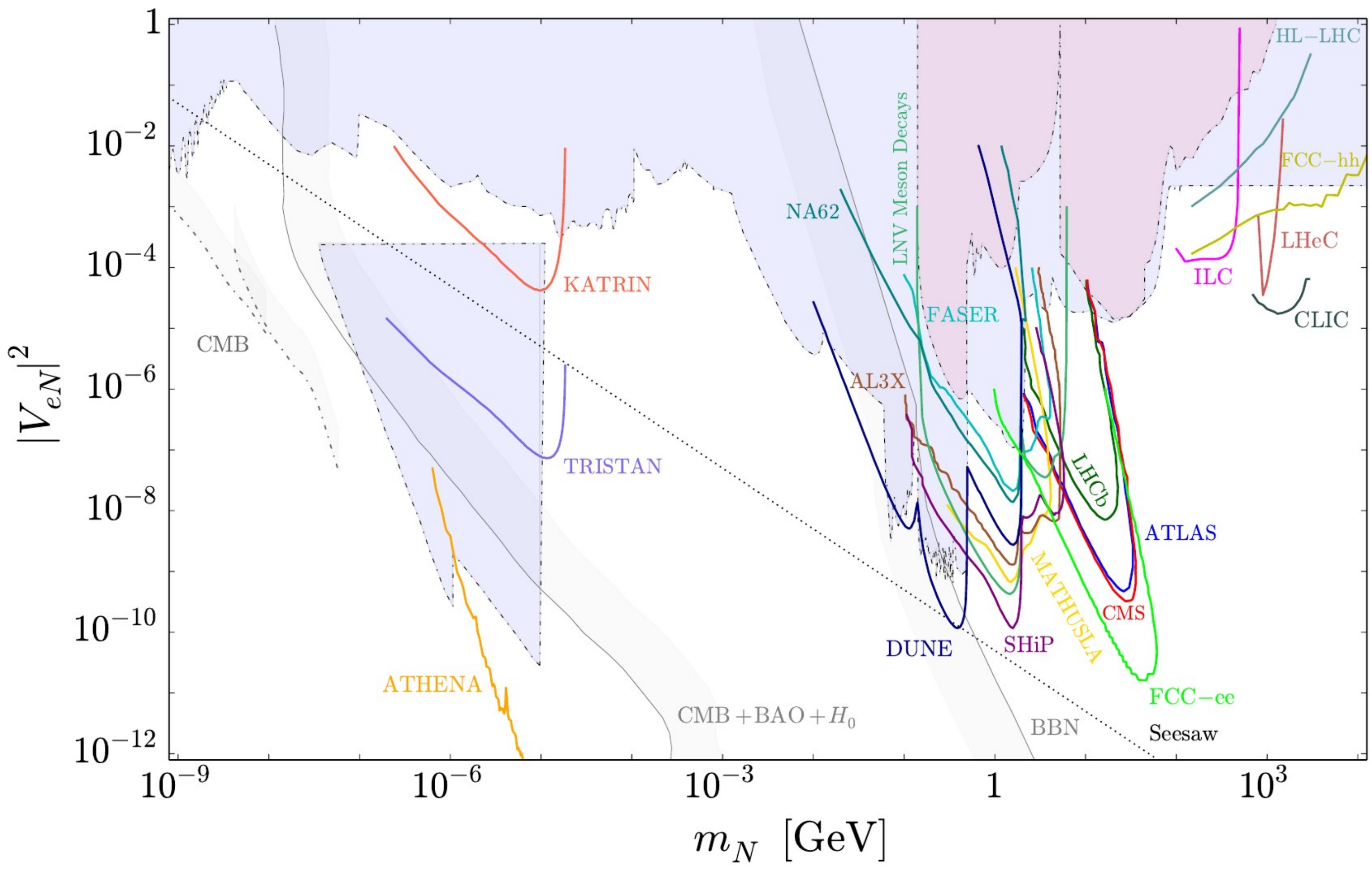
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}_N^{0\nu}|^2 \left| \sum_{i=1}^{3} \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



Bolton, Deppisch, Dev (2019)
Atre, Han, Pascoli, Zhang (2009)

Heavy Sterile Neutrinos

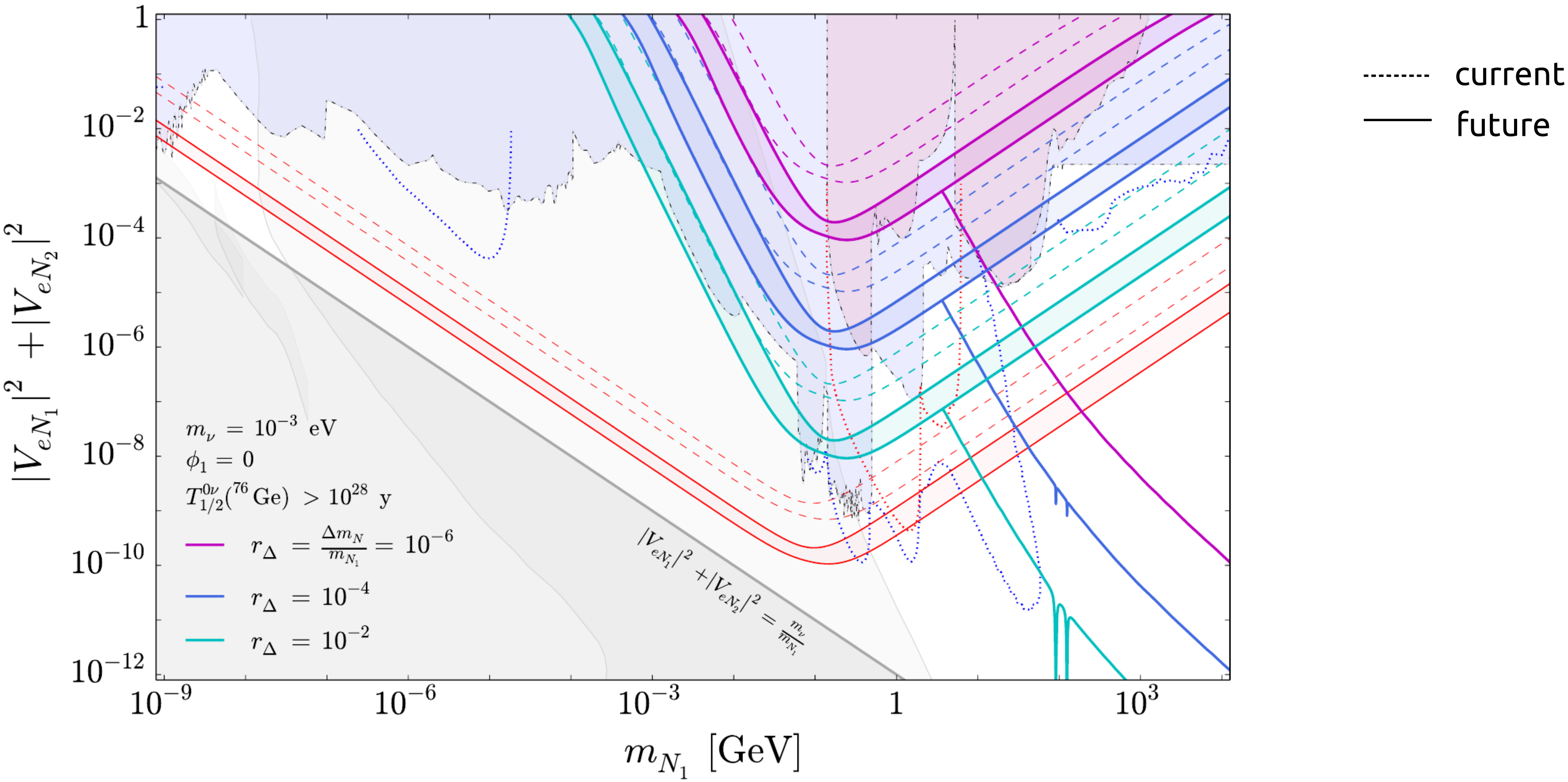
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}_N^{0\nu}|^2 \left| \sum_{i=1}^{3} \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



Bolton, Deppisch, Dev (2019)

Heavy Sterile Neutrinos

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}_N^{0\nu}|^2 \left| \sum_{i=1}^{3} \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



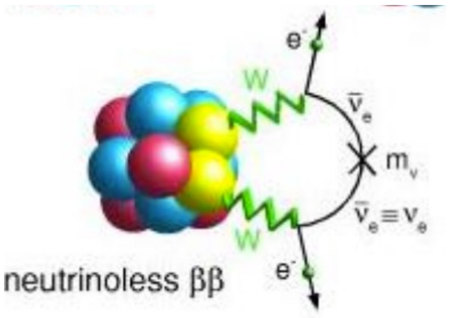
Δr → 0 leads to **pseudo-Dirac limit** where lepton number is approximately conserved and 0νββ forbidden

Bolton, Deppisch, Dev (2019)

Conclusions

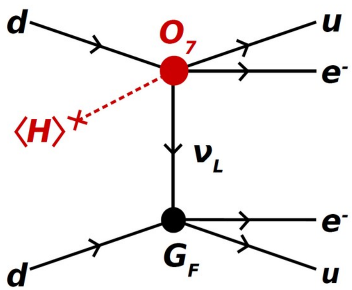
Summary

- $0\nu\beta\beta$ has huge potential to probe **LNV** and a **Majorana nature** of the neutrino
- Combination with **neutrino oscillations** powerful to constrain specific models
- Many **non-standard contributions** possible, many **topologies** and UV completions
- **$0\nu\beta\beta$ and LHC** compete against better sensitivity
- **QCD running** is important and can affect conclusions → "master formula"
- $0\nu\beta\beta$ can shed light on **baryogenesis**
- Many ideas to **disentangle different contributions**
- Open questions & uncertainties in **nuclear physics**



Thank you for your attention!

0νββ and Baryogenesis



$$T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2$$

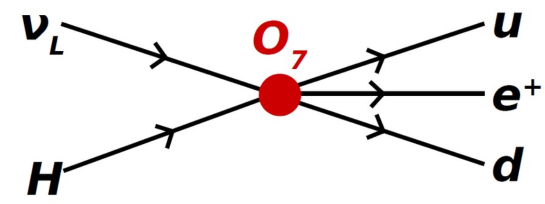
Observation would fix the **effective coupling** for one operator

$\mathcal{O}$	Operator
1^{H^2}	$L^iL^jH^kH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$
4_a	$L^iL^j\overline{Q}_i\bar{u^c}H^k\epsilon_{jk}$
$4_b^\dagger$	$L^iL^j\overline{Q}_k\bar{u^c}H^k\epsilon_{ij}$
8	$L^i\bar{e^c}\bar{u^c}d^cH^j\epsilon_{ij}$

$$\frac{G_F\epsilon_7}{\sqrt{2}} = \frac{g^3v}{2\Lambda_7{}^3}$$

effective coupling can be related to the **scale of the operator**

$\mathcal{O}_D$	Λ_D^0 [GeV]
$\mathcal{O}_5$	9.1×10^{13}
$\mathcal{O}_7$	2.6×10^{4}
$\mathcal{O}_9$	2.1×10^{3}
$\mathcal{O}_{11}$	1.0×10^{3}



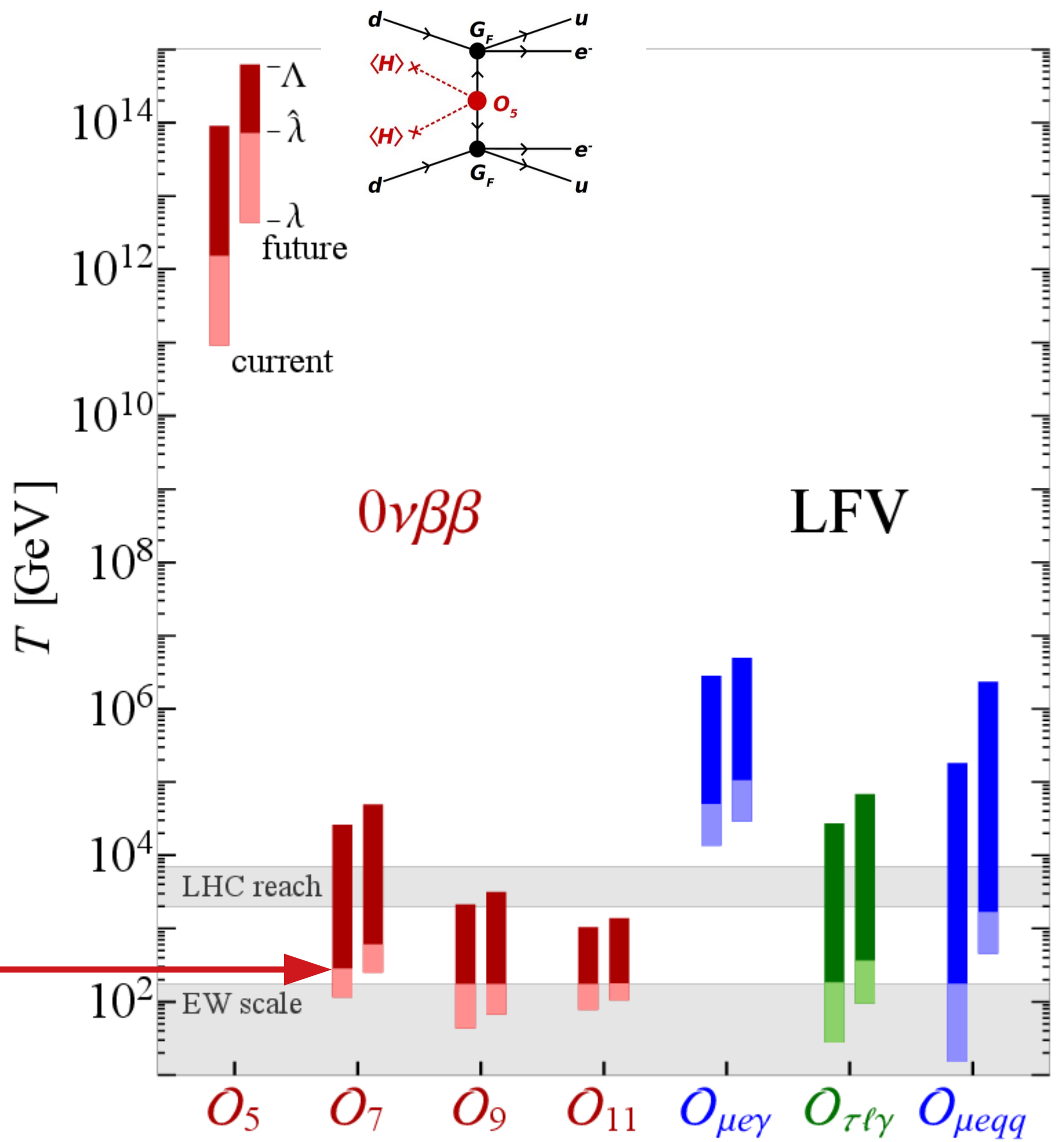
$$\frac{\Gamma_W}{H} > 1$$

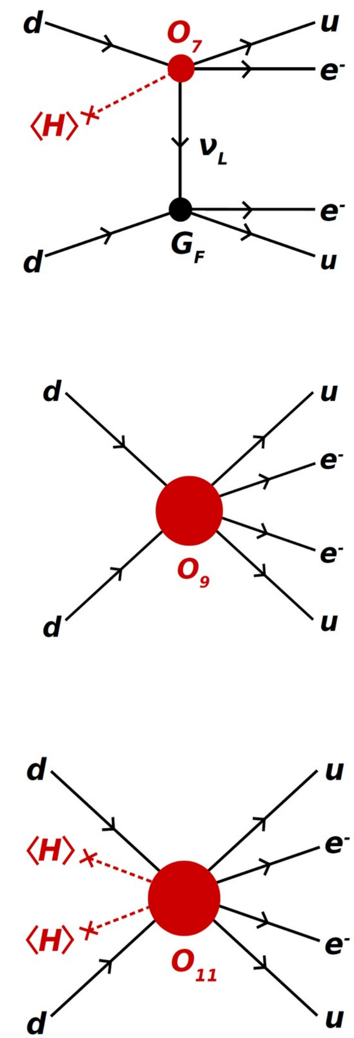
$$\Lambda_7\left(\frac{\Lambda_7}{c_7'\Lambda_{Pl}}\right)^{\frac{1}{5}}\lambda_7 < T < \Lambda_7$$

Limit above which the washout is highly effective can be calculated in dependence of the **operator scale**

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

0νββ and Baryogenesis





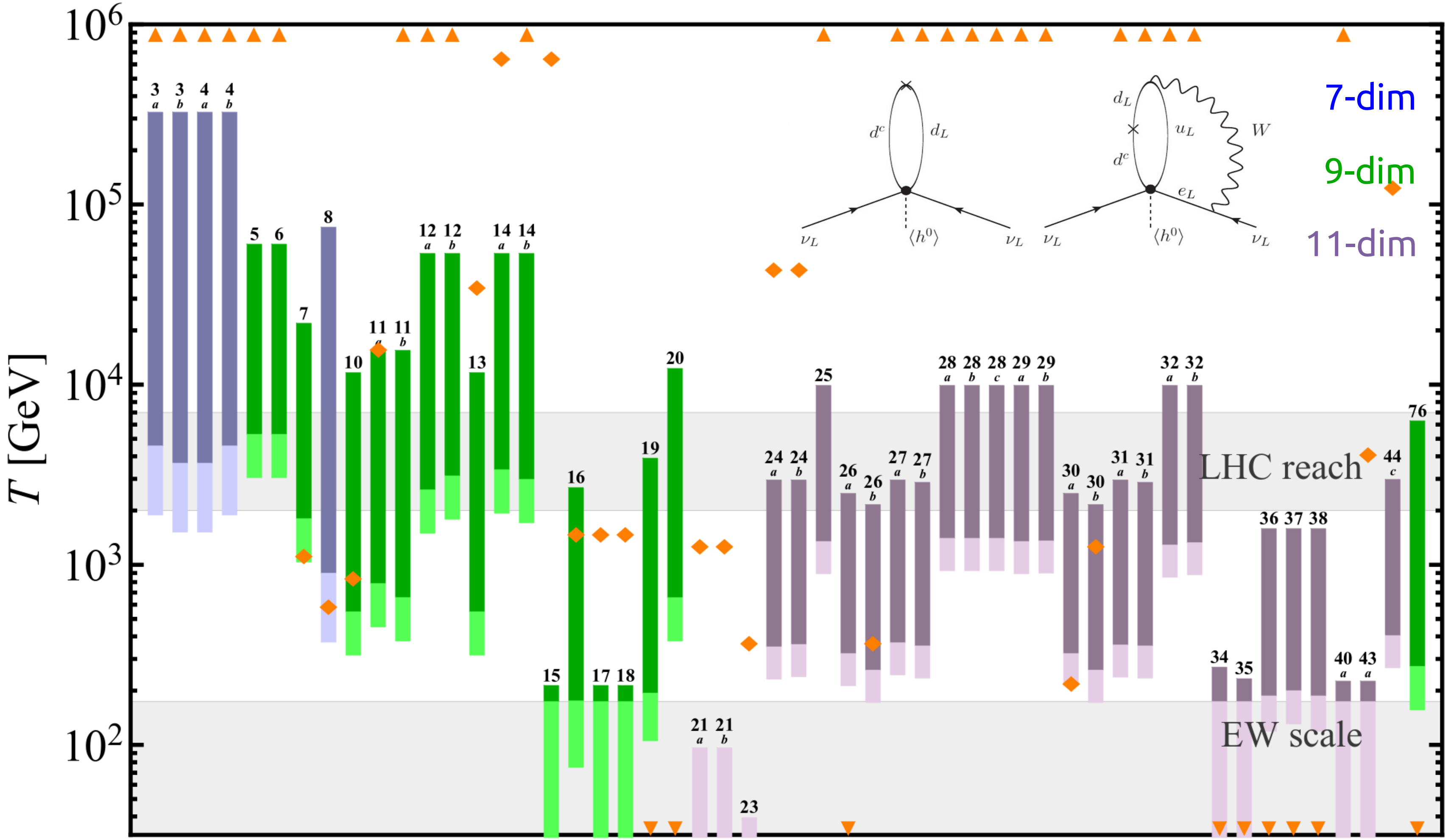
limit above which the washout is highly effective

$$\frac{\Gamma_W}{H} > 1$$

Potential to falsify baryogenesis models!

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

0νββ and Baryogenesis



Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Side remark: **Loop enhanced** rate of neutrinoless double beta decay via **virtuality** of the particle in the loop

Rodejohann, Xu (2019)

Putting pieces together

1st generation couplings

$\mathcal{O}$	$1/\Lambda^2_{K\to\pi\nu\nu}$	$\sum_i \Lambda^{\text{E949}}_{iisd}$ [TeV]	m_ν	Λ^{m_ν} [TeV]
1^{y_d}	$\frac{v^3}{\Lambda^5}$	2.4	$\frac{y_d}{16\pi^2}\frac{v^4}{\Lambda^3}$	11.6
$3b$	$\frac{v}{\Lambda^3}$	11.5	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}$	5.2×10^4
$3b^{H^2}$	$f(\Lambda)\frac{v}{\Lambda^3}$	5.7	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	330
5	$\frac{1}{16\pi^2}\frac{v}{\Lambda^3}$	2.6	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	330
10	$\frac{1}{16\pi^2}\frac{y_e v}{\Lambda^3}$	0.8	$\frac{y_e y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	9.6×10^{-4}
$11b$	$\frac{1}{16\pi^2}\frac{y_d v}{\Lambda^3}$	0.8	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	8.9×10^{-3}
$14b$	$\frac{1}{16\pi^2}\frac{y_u v}{\Lambda^3}$	2.9	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	4.1×10^{-3}
66	$f(\Lambda)\frac{v}{\Lambda^3}$	5.1	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	330

Sensitivity to different flavors than most constraining 0νββ !

Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\text{NP}}_{ijkn}$ [TeV]
$K^+\to\pi^+\nu\nu$	$\text{BR}^{\text{NA62}}_{\text{future}} < 1.11\times10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i\Lambda_{iisd} > 19.6$
$K^+\to\pi^+\nu\nu$	$\text{BR}^{\text{NA62}}_{\text{current}} < 1.78\times10^{-10}$ [67]	$\mathcal{O}_{3b}$	$\sum_i\Lambda_{iisd} > 17.2$
$K_L\to\pi^0\nu\nu$	$\text{BR}^{\text{KOTO}}_{\text{current}} < 3.0\times10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i\Lambda_{iisd} > 12.3$